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Yuan et al.

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(54) **CHARGE REDISTRIBUTION DURING ERASE
IN CHARGE TRAPPING MEMORY**

(71) Applicant: **SanDisk Technologies Inc.**, Plano, TX
(US)

(72) Inventors: **Jiahui Yuan**, Fremont, CA (US);
Ching-Huang Lu, Fremont, CA (US);
Yingda Dong, San Jose, CA (US)

(73) Assignee: **SanDisk Technologies Inc.**, Plano, TX
(US)

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G11C 16/14 (2006.01)
G11C 16/26 (2006.01)
G11C 16/34 (2006.01)

(52) **U.S. Cl.**
CPC **G11C 16/14** (2013.01); **G11C 16/0466**
(2013.01); **G11C 16/26** (2013.01); **G11C**
16/3445 (2013.01)

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CPC **G11C 16/0483**; **G11C 16/16**; **G11C 16/14**;
G11C 16/344; **G11C 11/5628**; **G11C 16/10**;
G11C 16/3454
USPC **365/185.29**, **185.17**, **185.19**, **185.22**
See application file for complete search history.

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Primary Examiner — David Lam

(74) *Attorney, Agent, or Firm* — Vierra Magen Marcus LLP

(57) **ABSTRACT**

Techniques are provided to accelerate the redistribution of the holes in connection with an erase operation, so that there will be a reduced amount of redistribution of the holes after programming. As a result, short-term charge loss after programming is reduced. In one aspect, a positive control gate voltage is applied to a set of memory cells after erase and before programming. The positive control gate voltage has a relatively low amplitude and a long duration, compared to a programming voltage. The positive control gate voltage can be adjusted based on the erase depth of the memory cells and factors such as a count of program-erase cycles, a count of erase-verify iterations, sensing of a position of the lower tail, and a cross-sectional width of a vertical pillar of a memory hole.

21 Claims, 15 Drawing Sheets

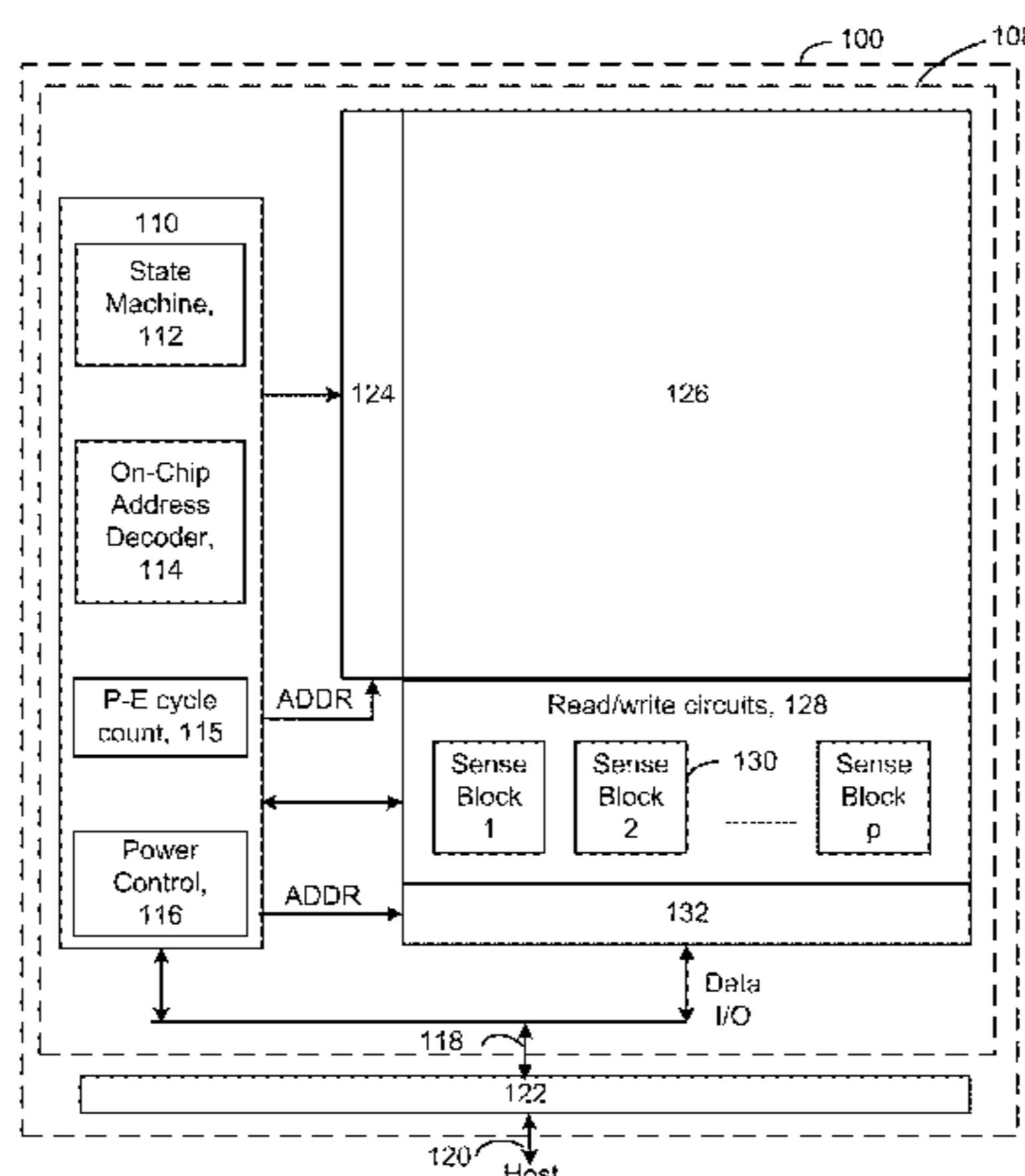


Fig. 1A

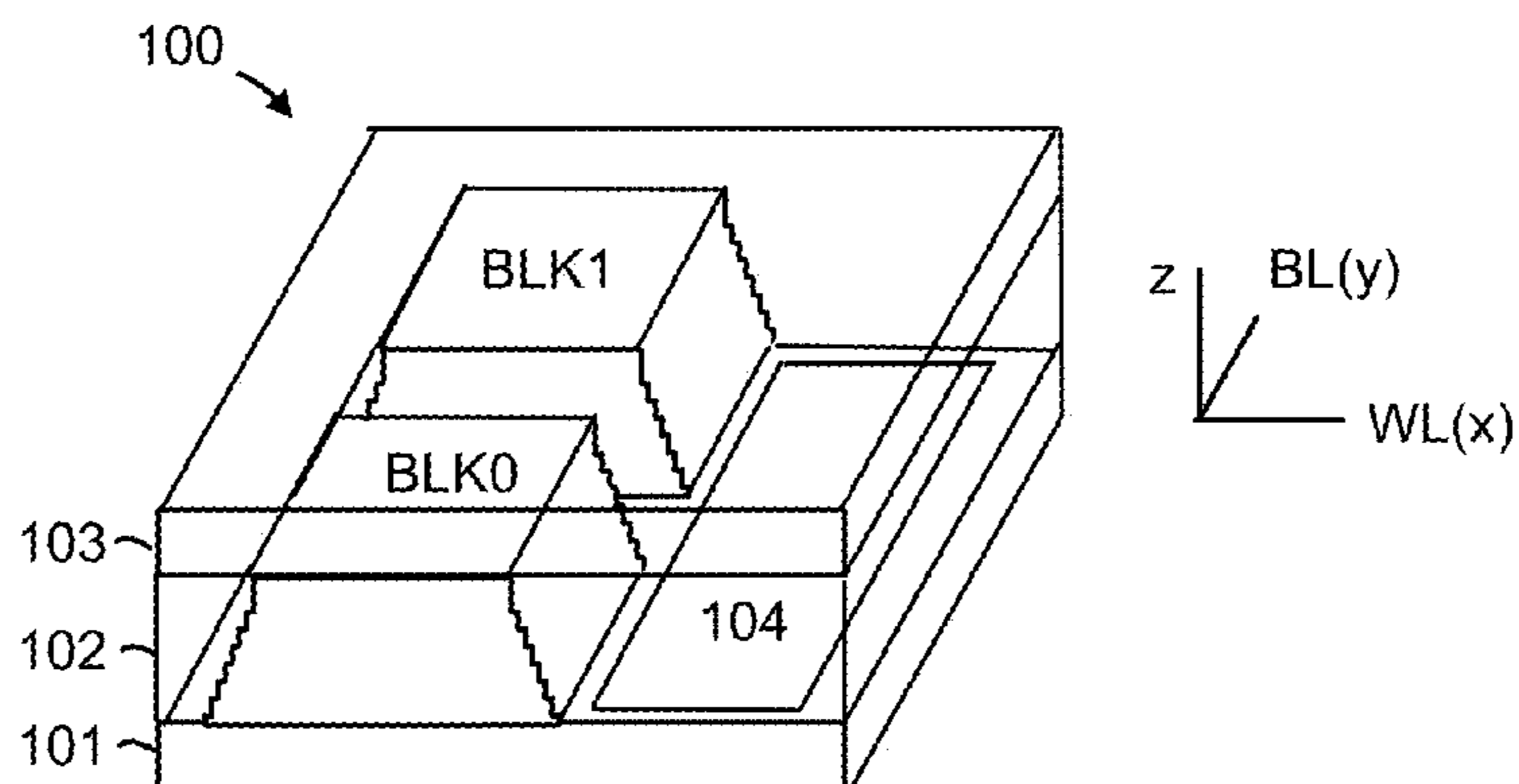
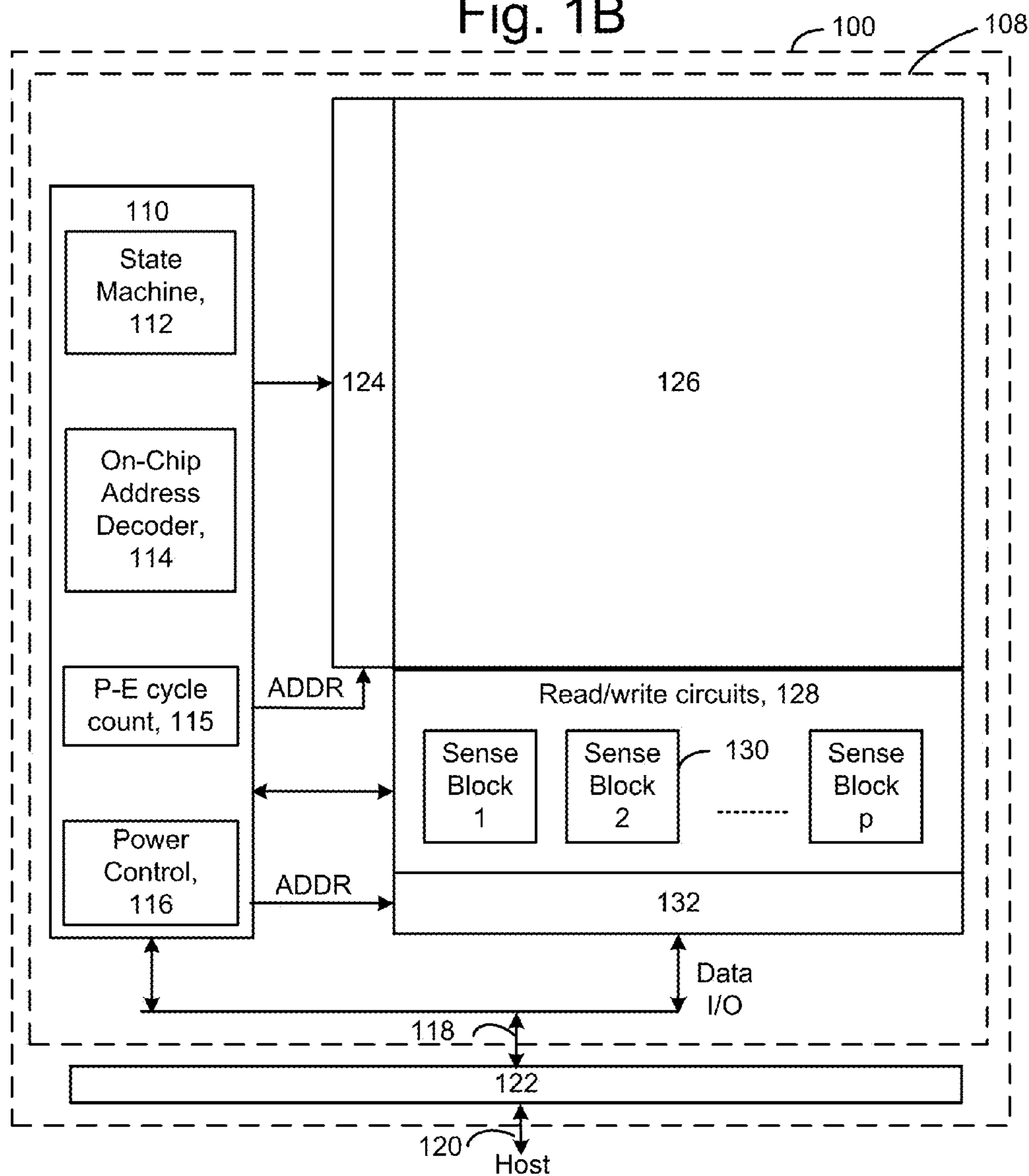


Fig. 1B



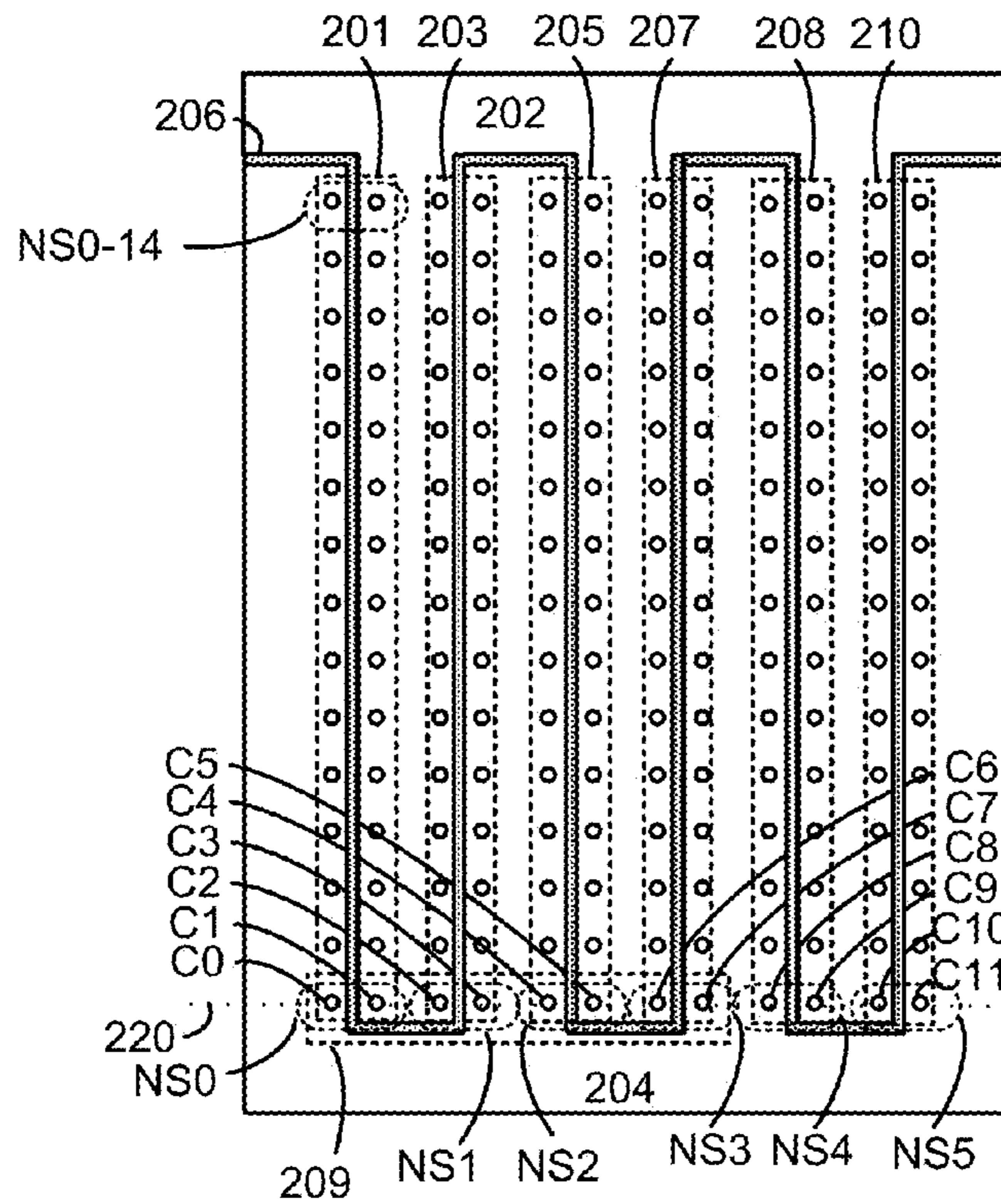


Fig. 2A

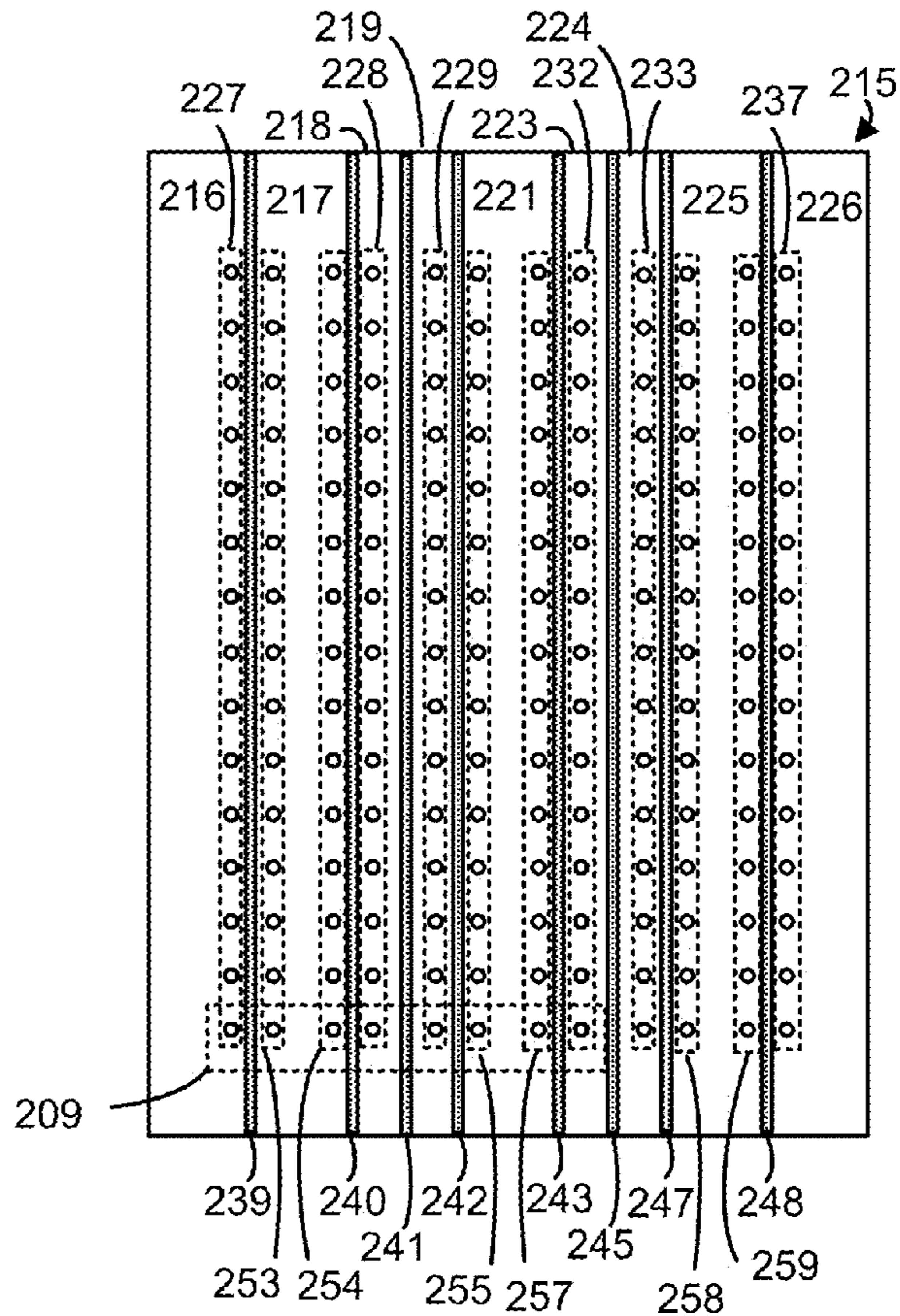
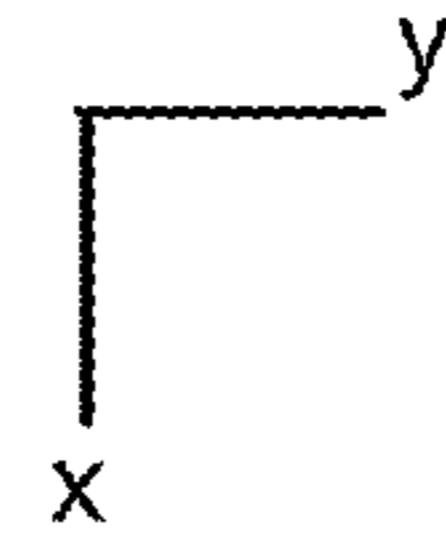


Fig. 2B

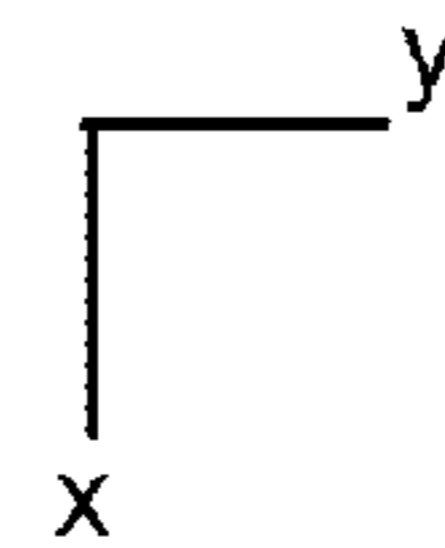
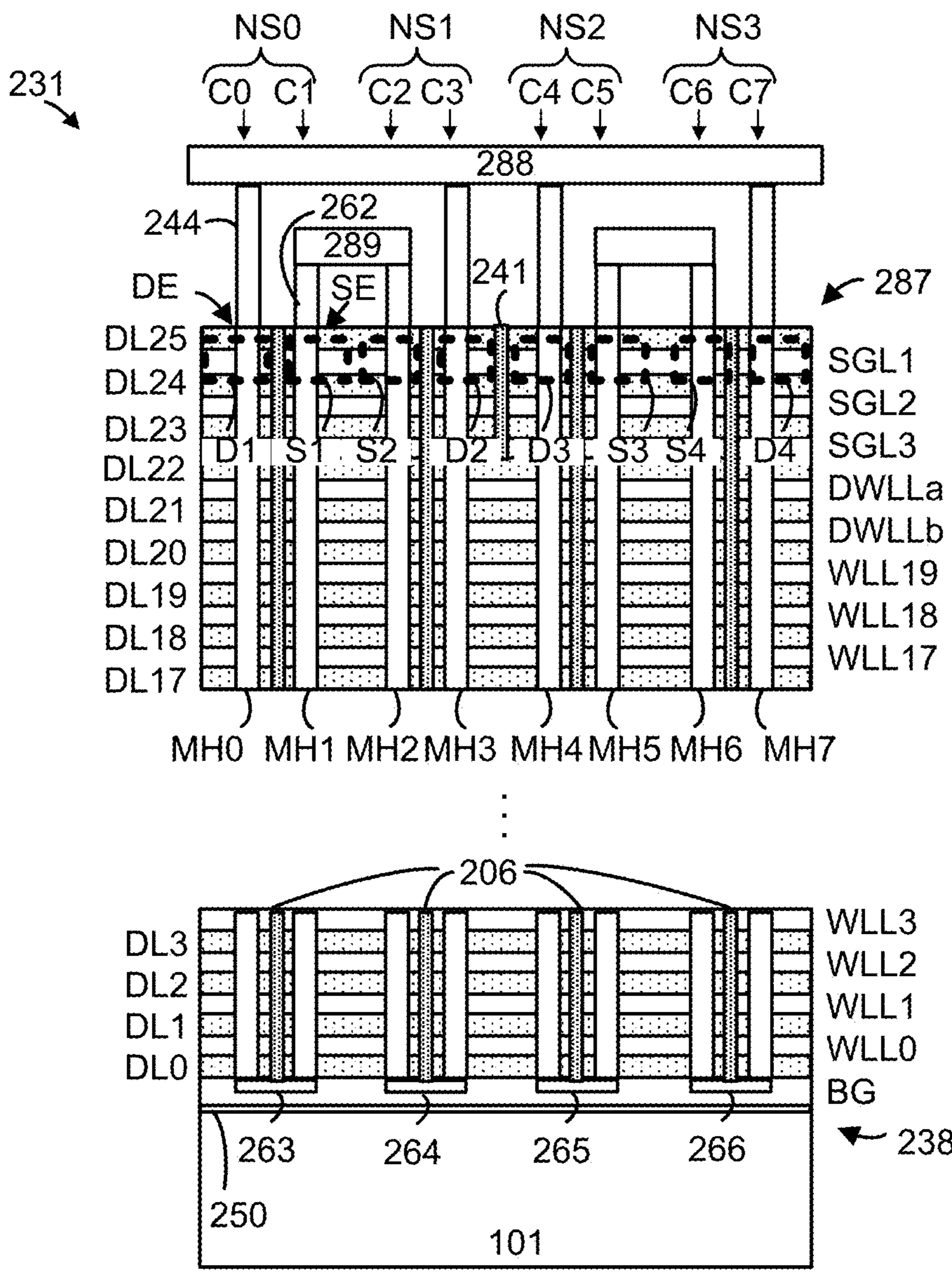
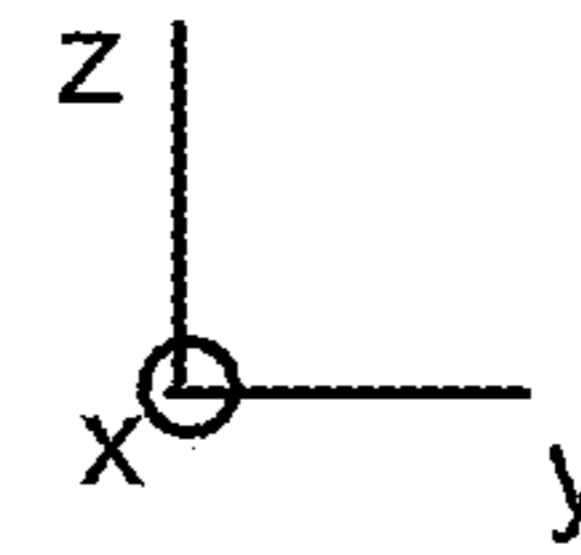


Fig. 2C



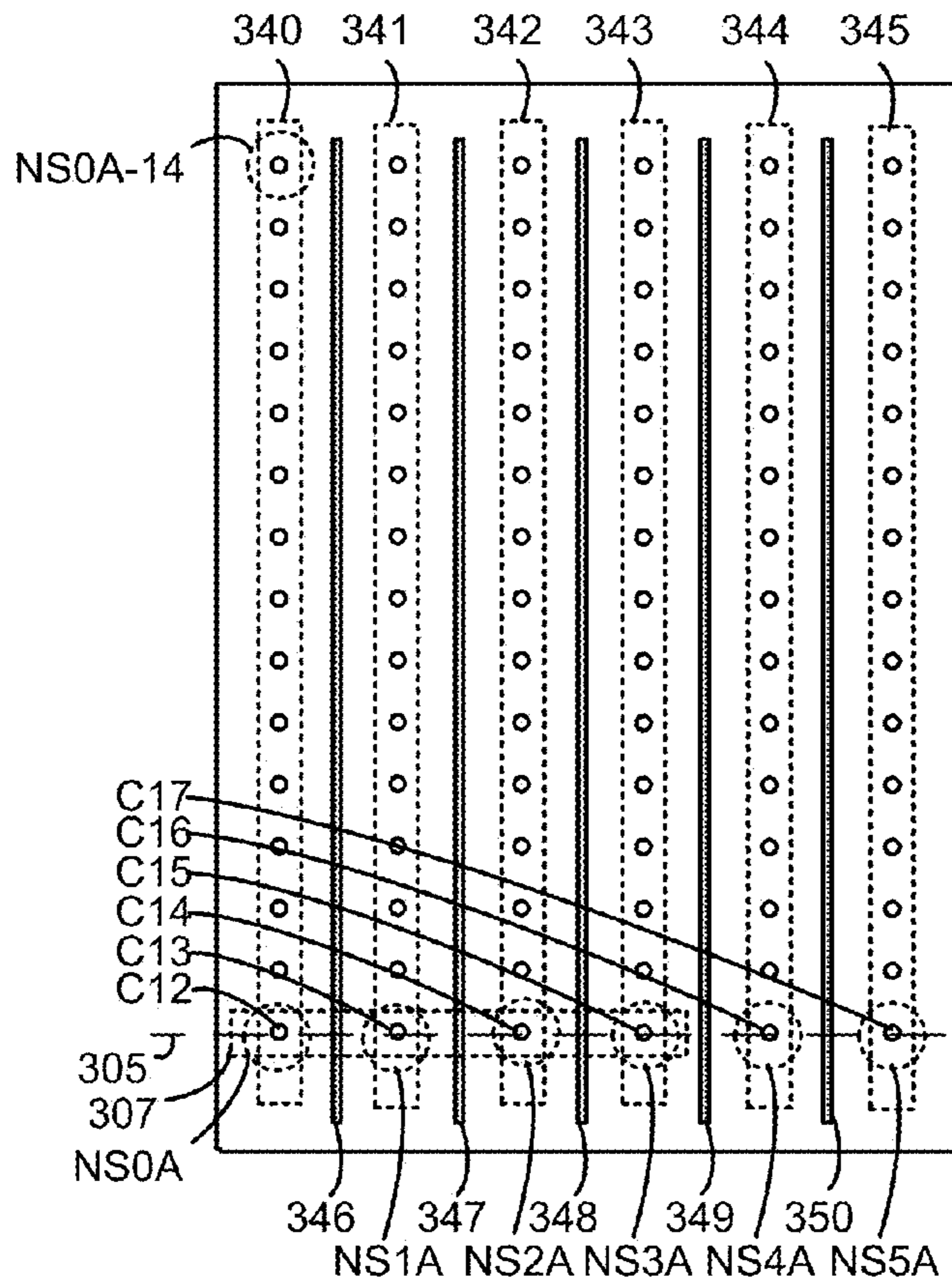


Fig. 3A

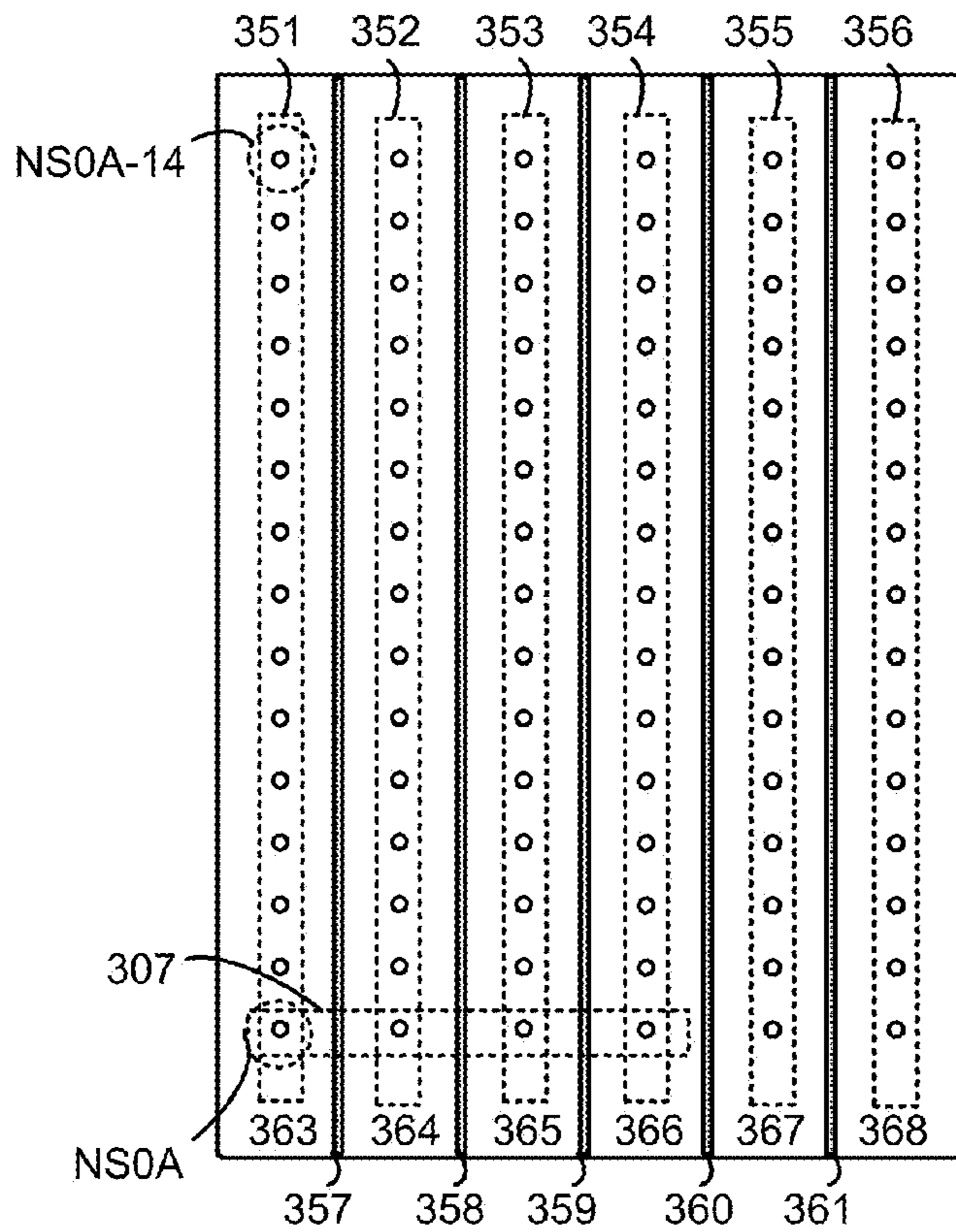
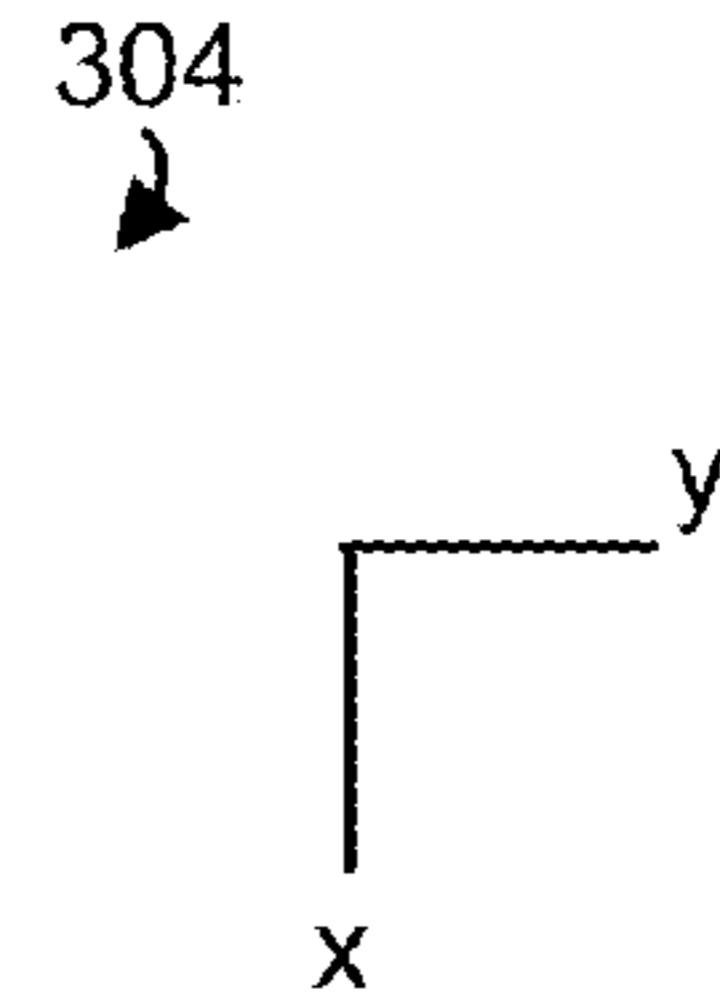


Fig. 3B

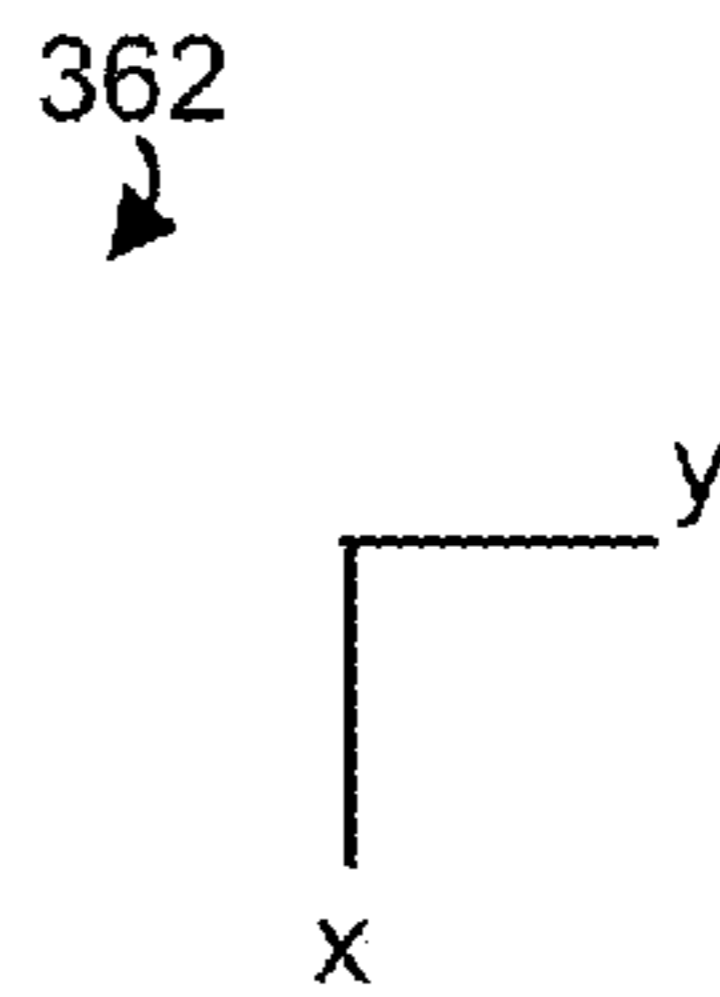


Fig. 3C1

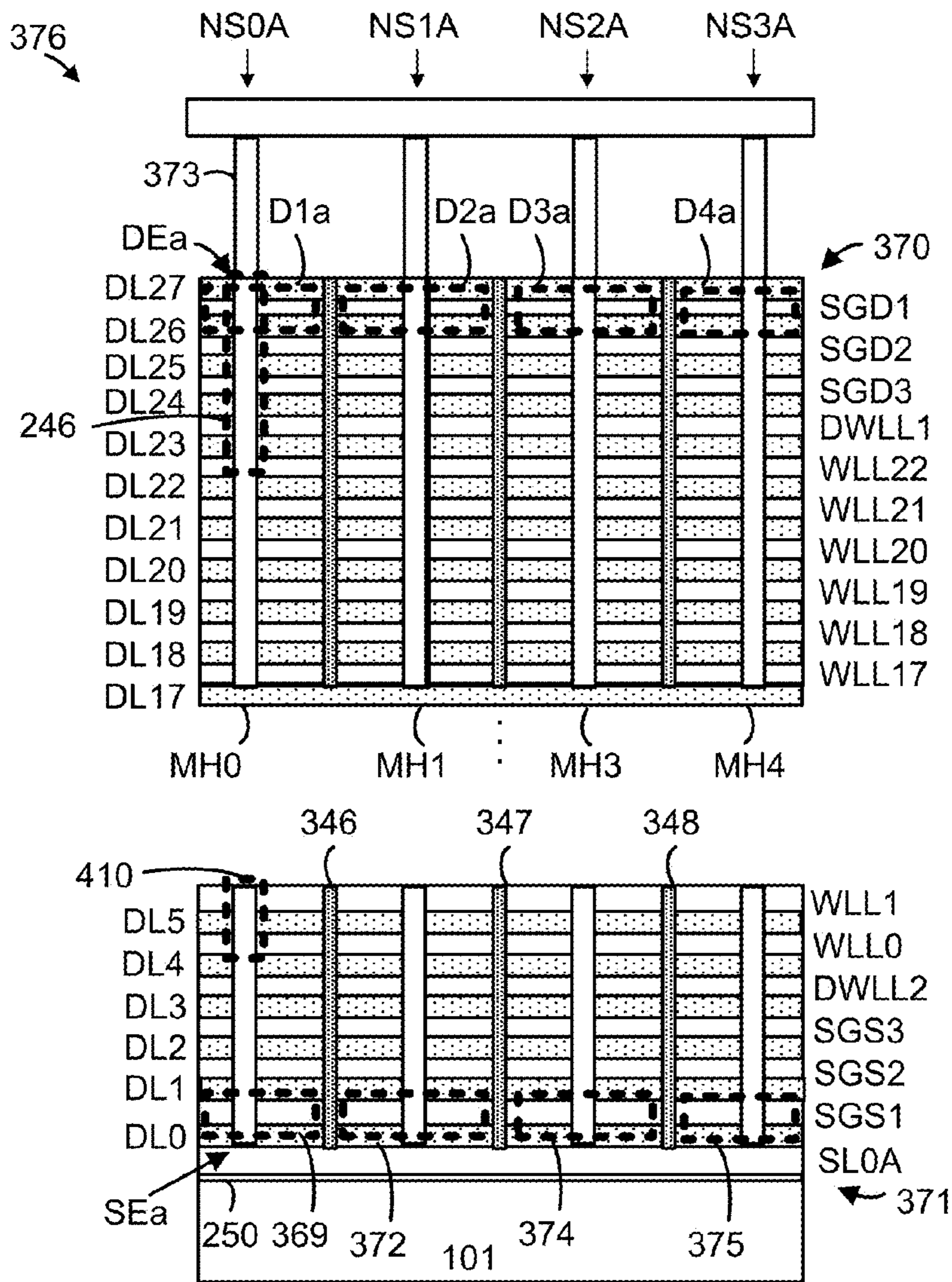
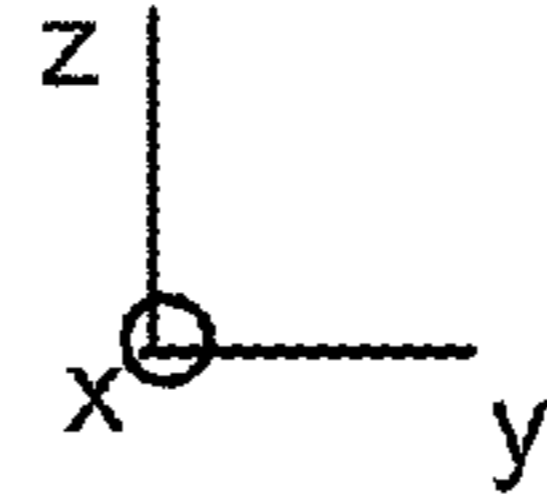
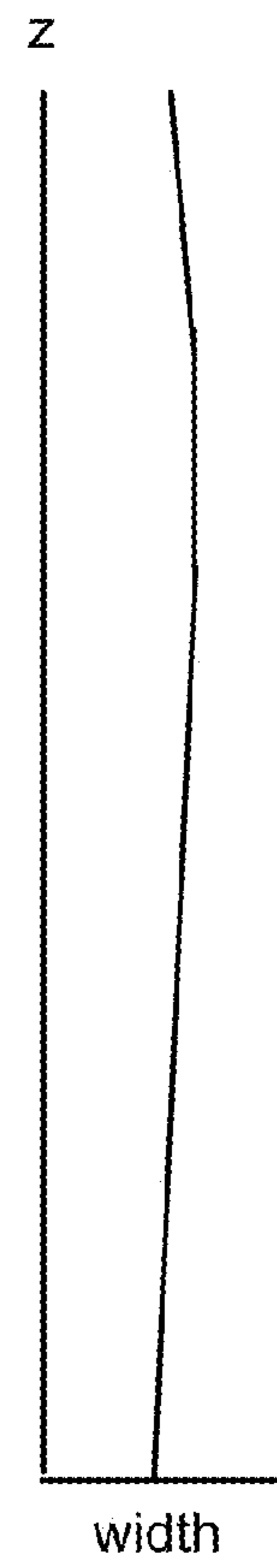


Fig. 3C2



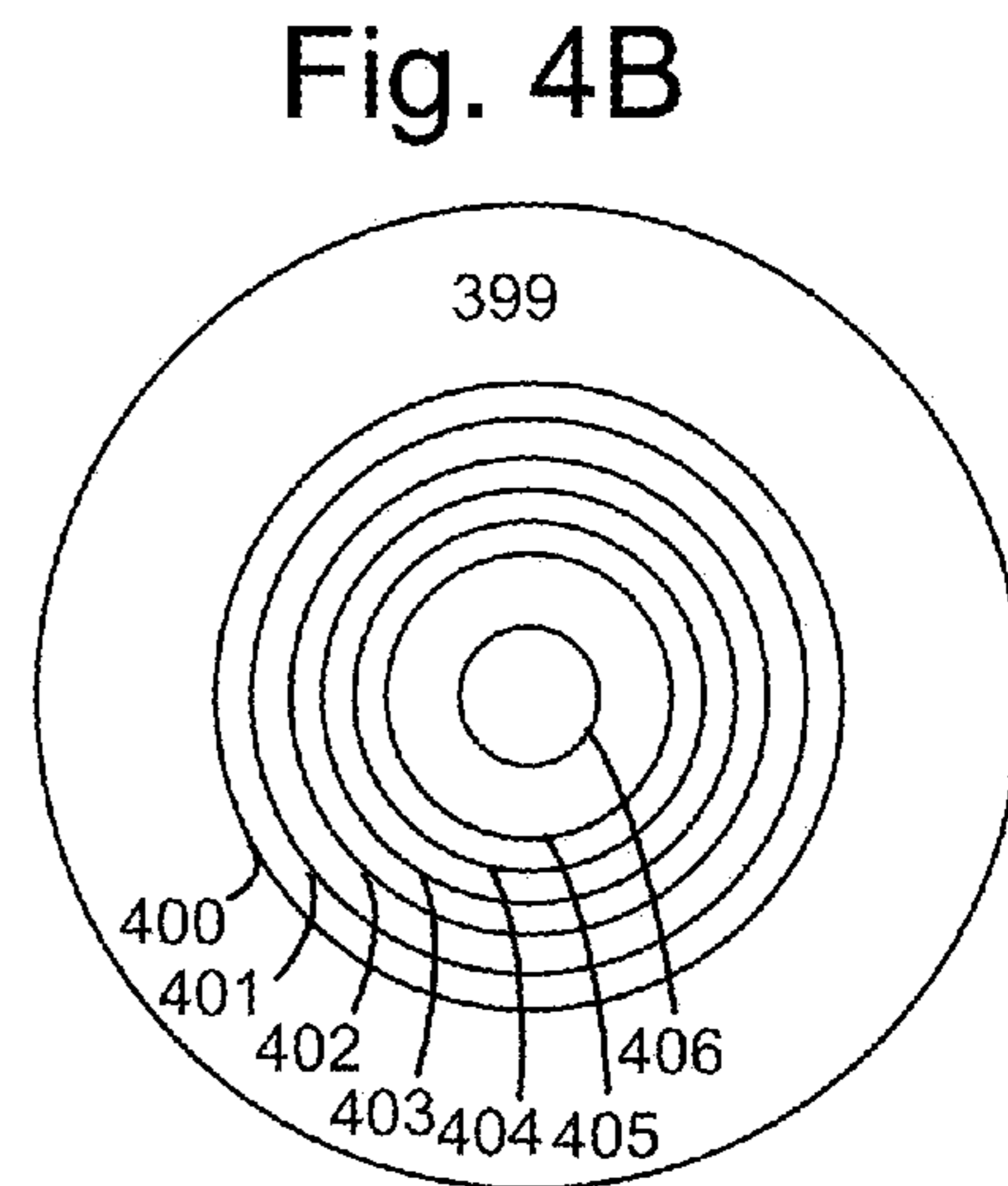
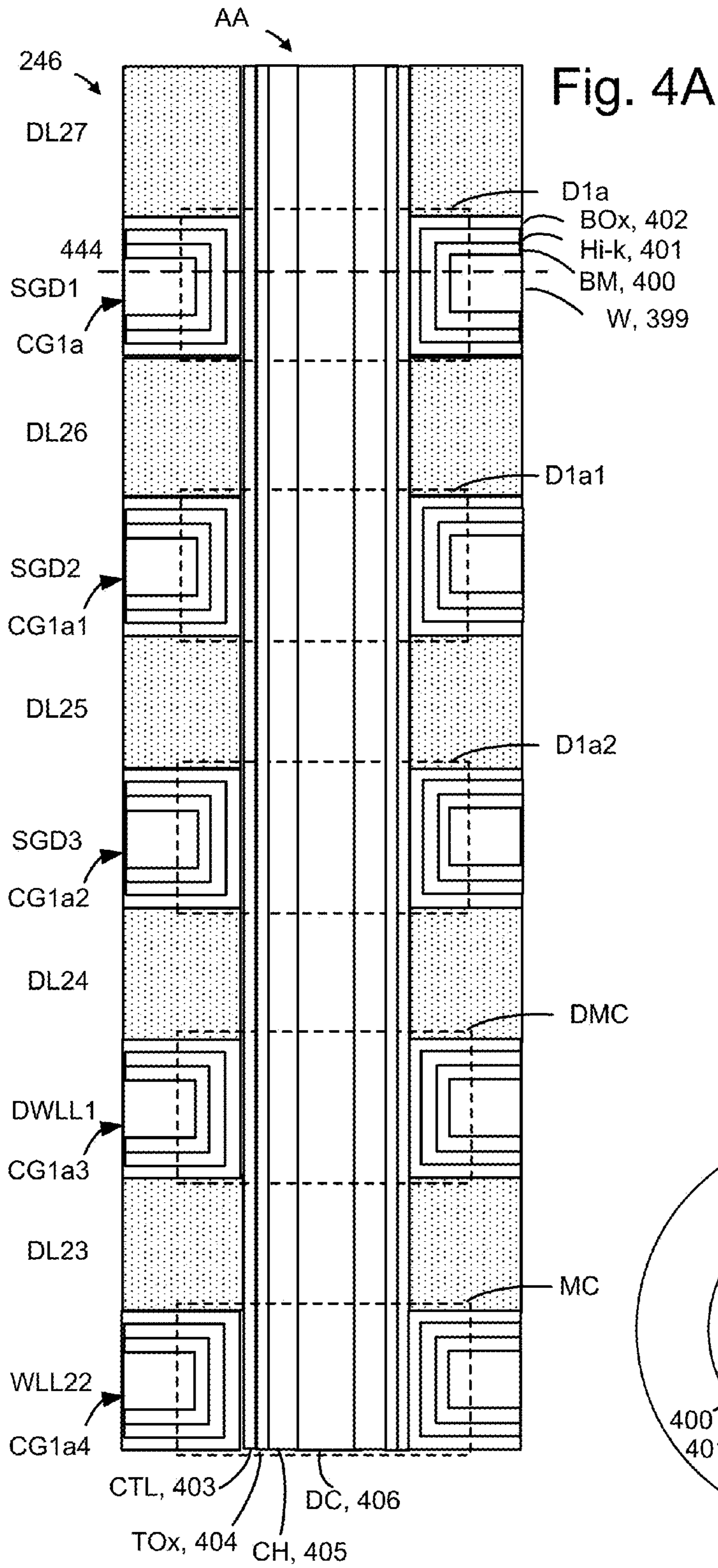


Fig. 4C

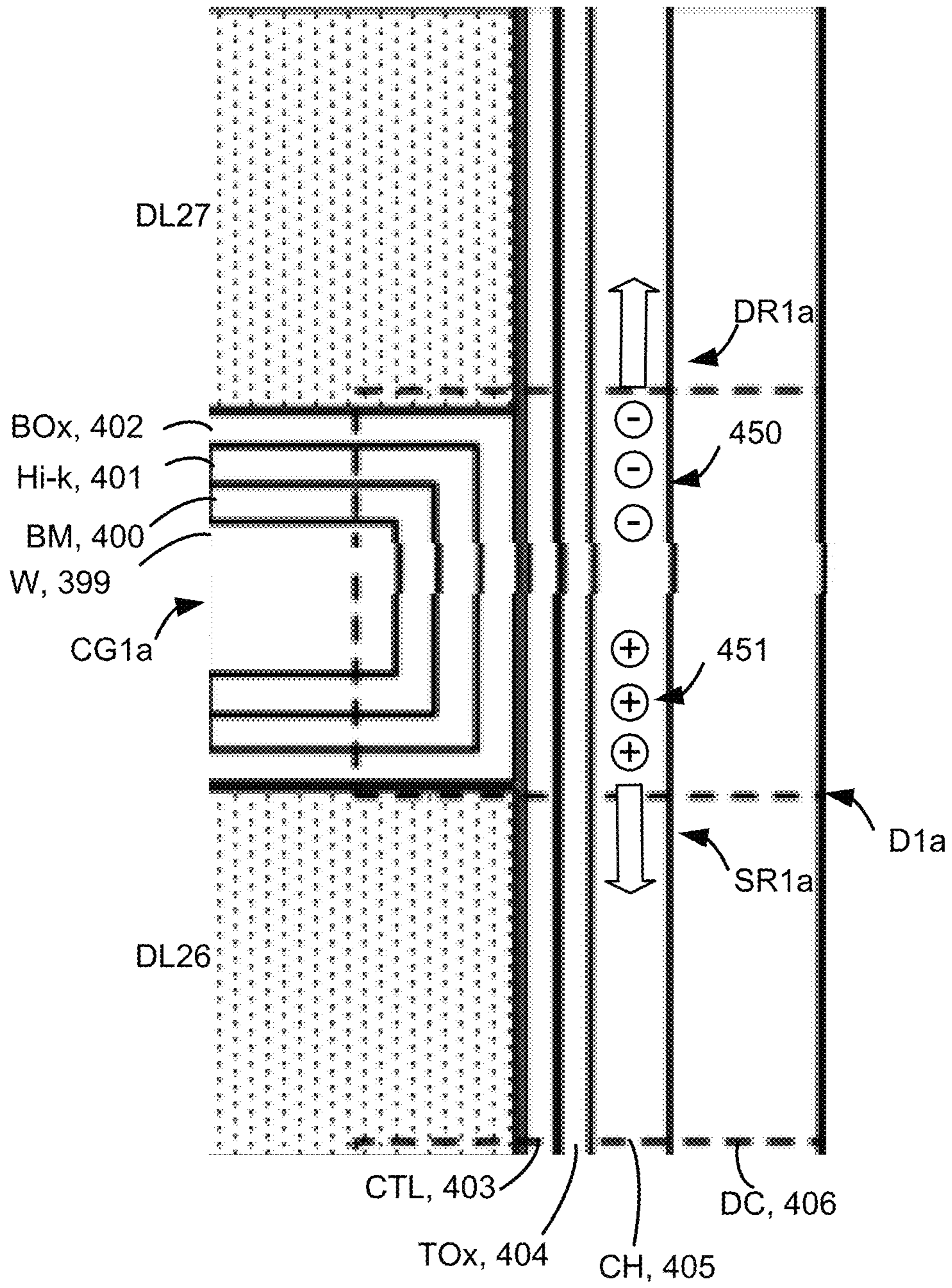


Fig. 4D

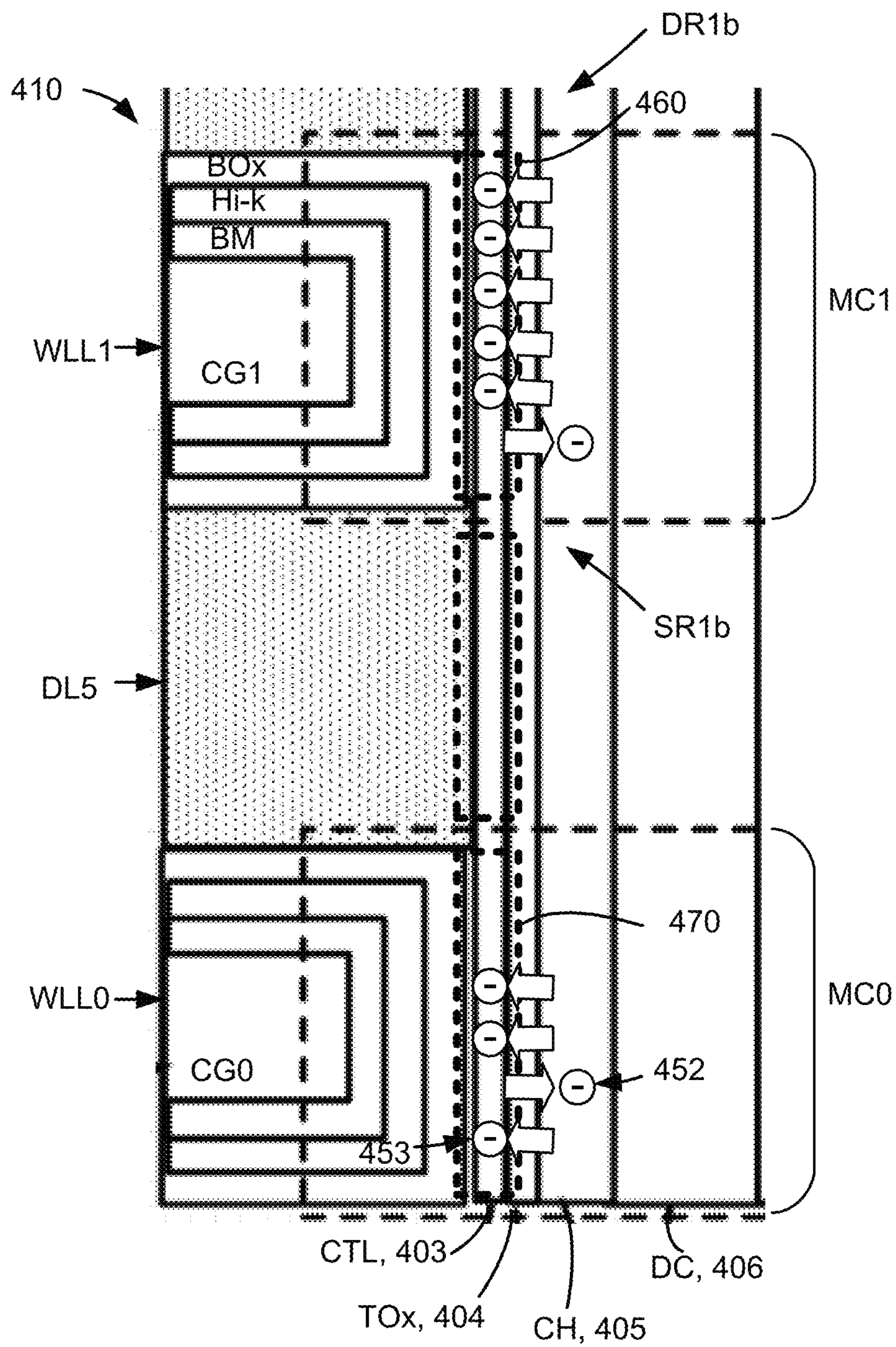


Fig. 5A

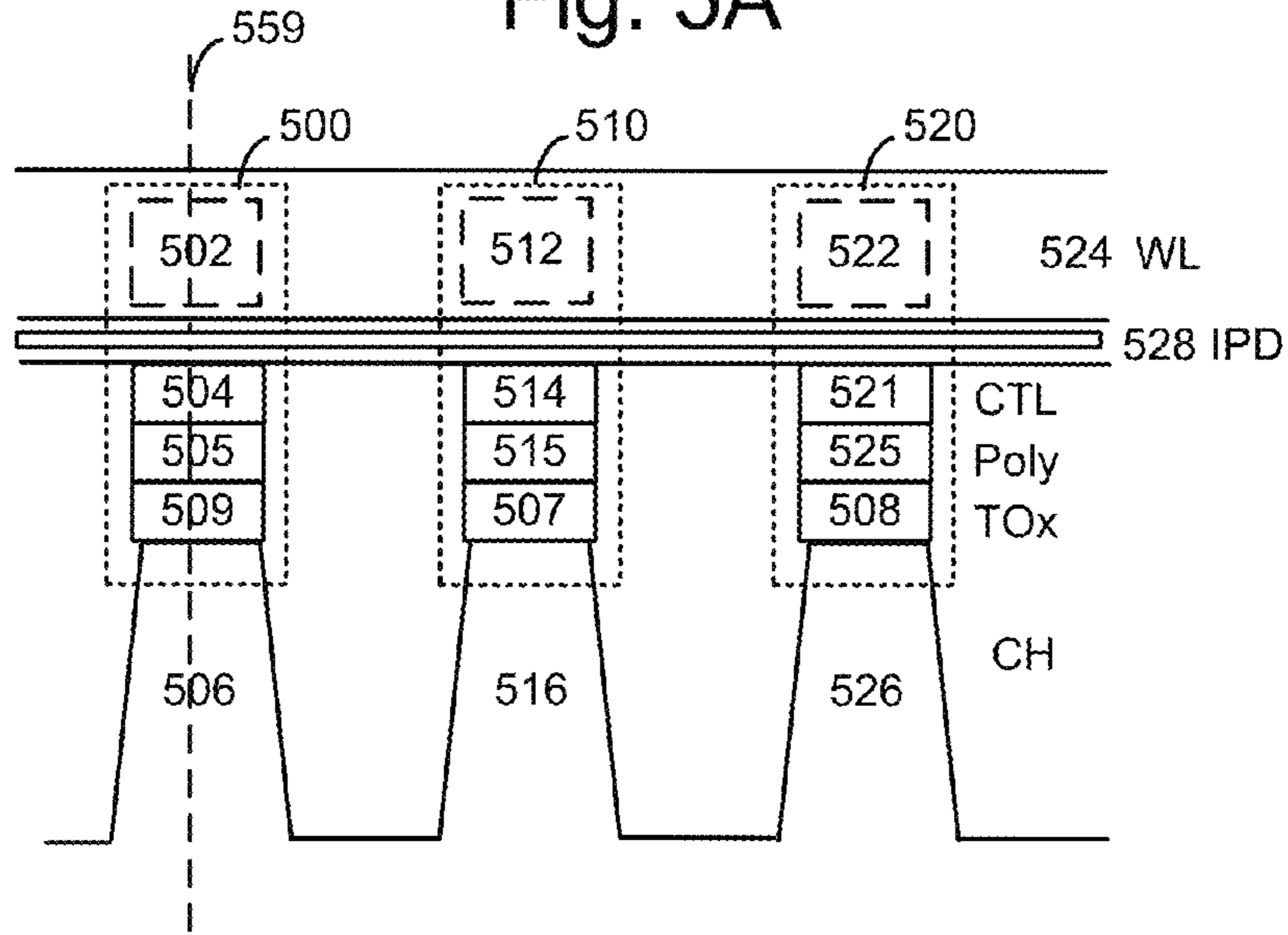


Fig. 5B

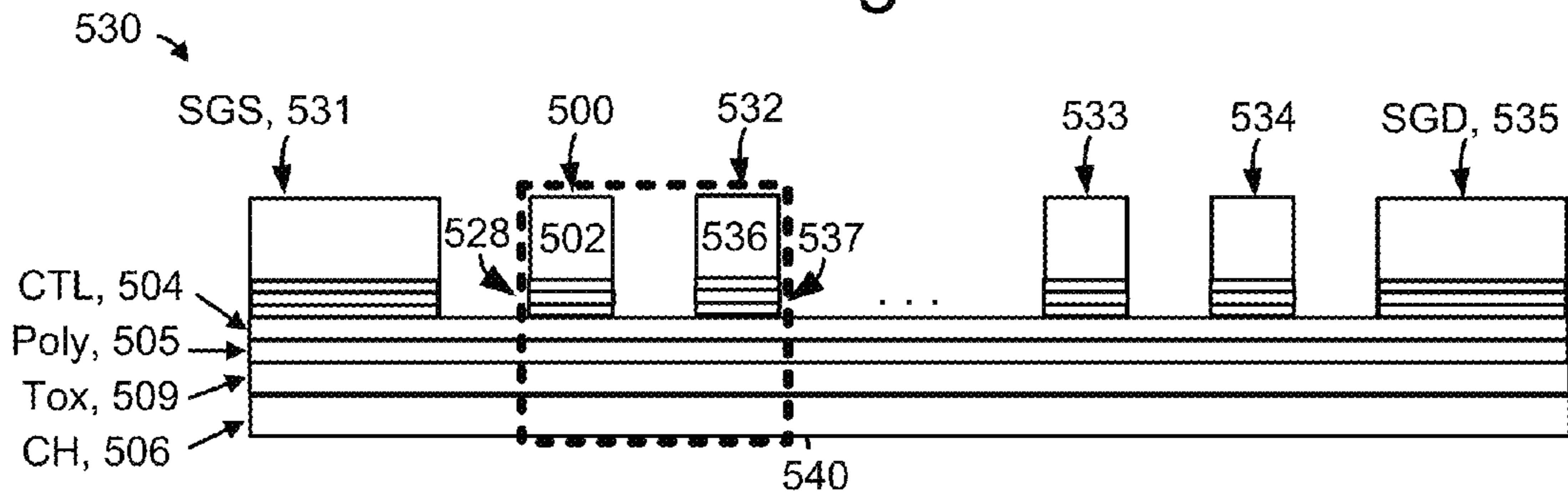


Fig. 5C

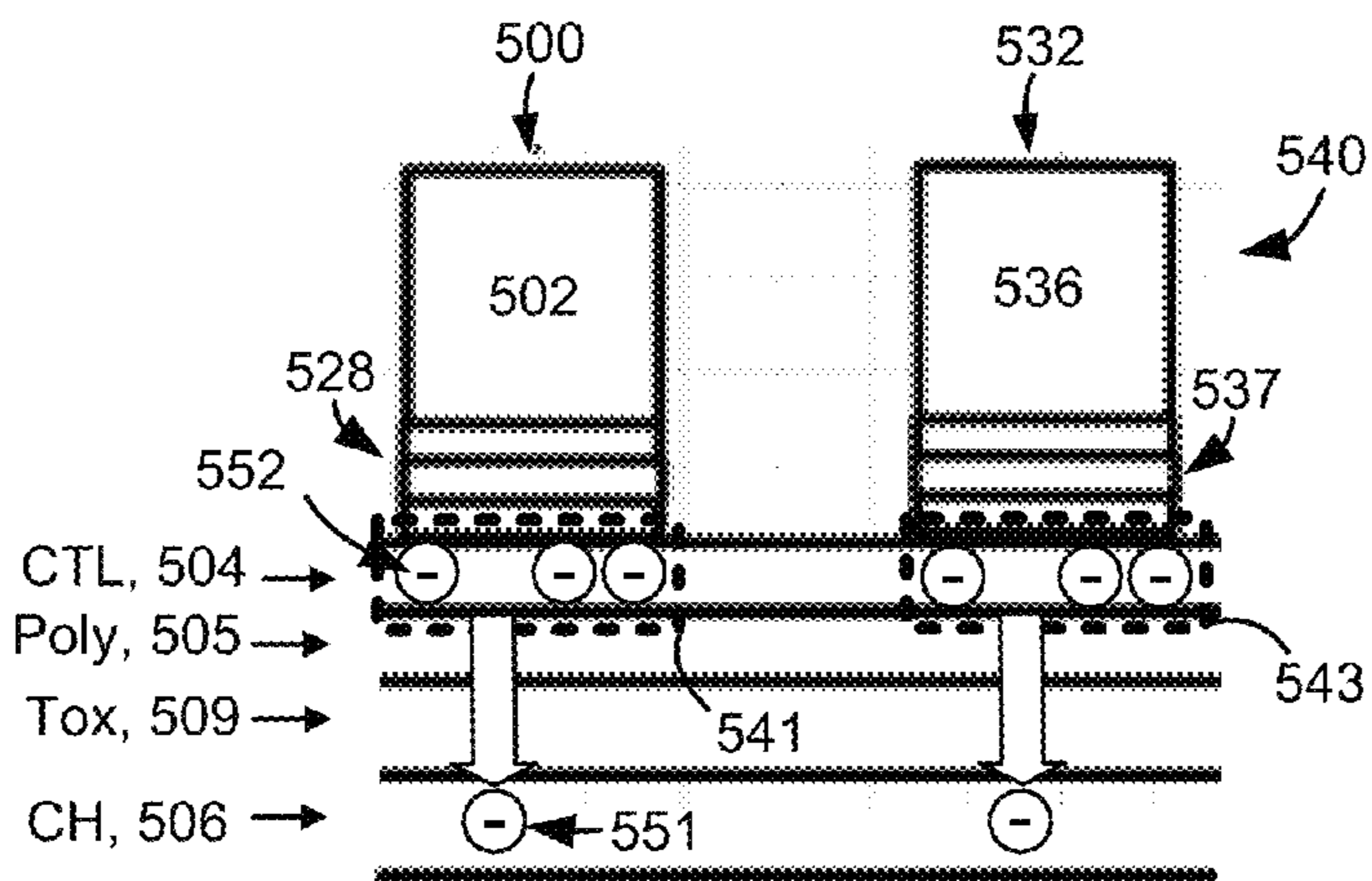


Fig. 6A

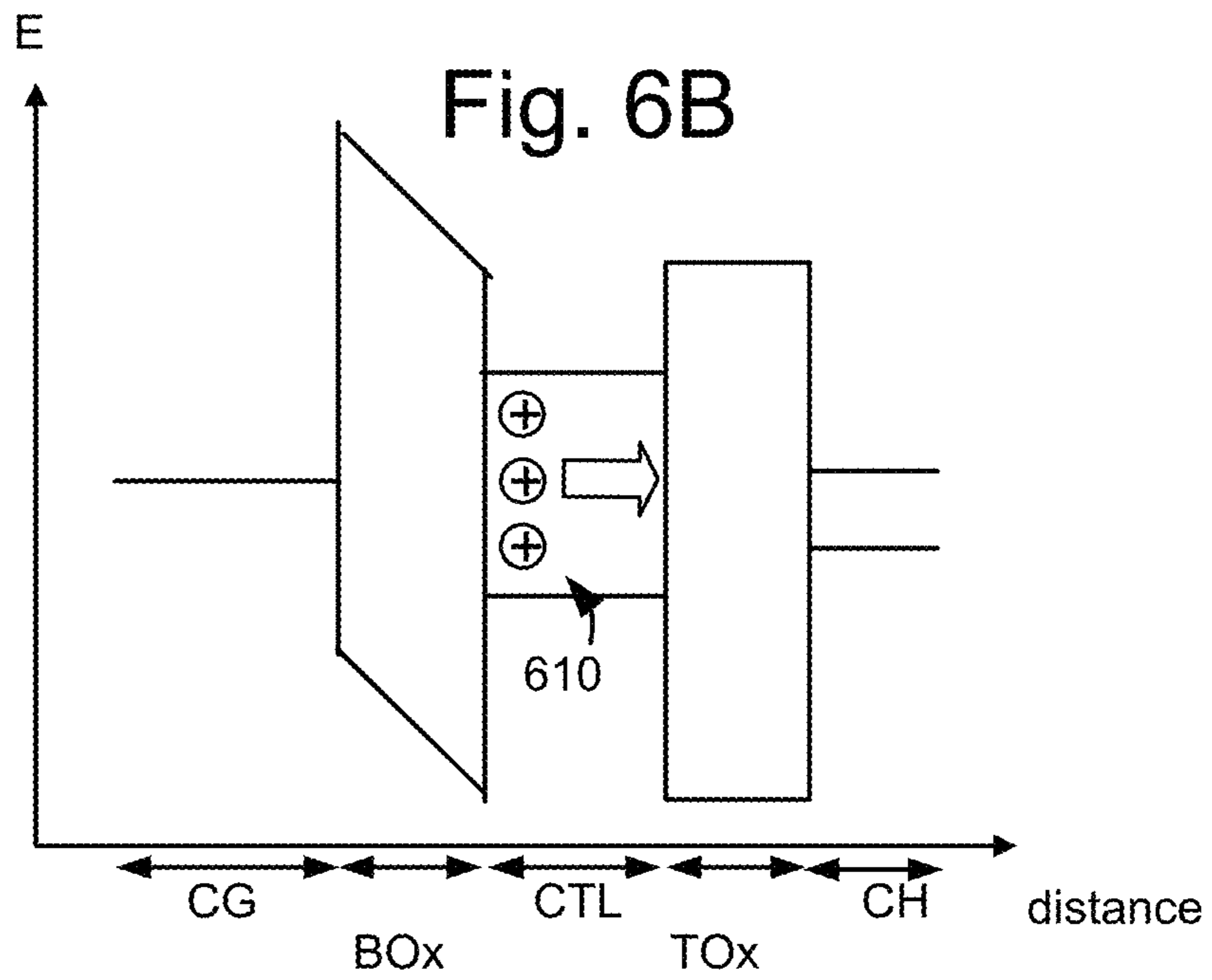
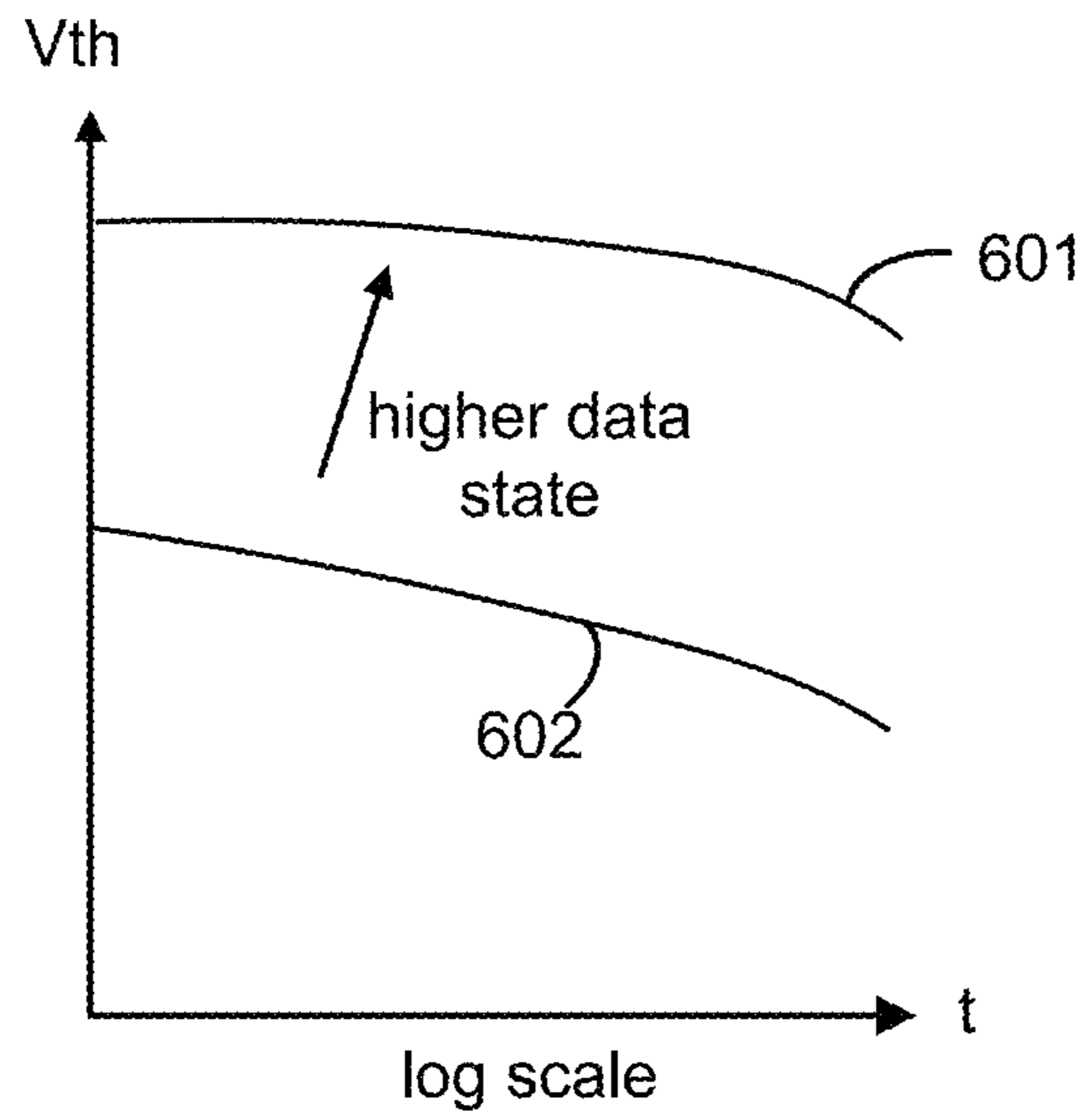


Fig. 7A

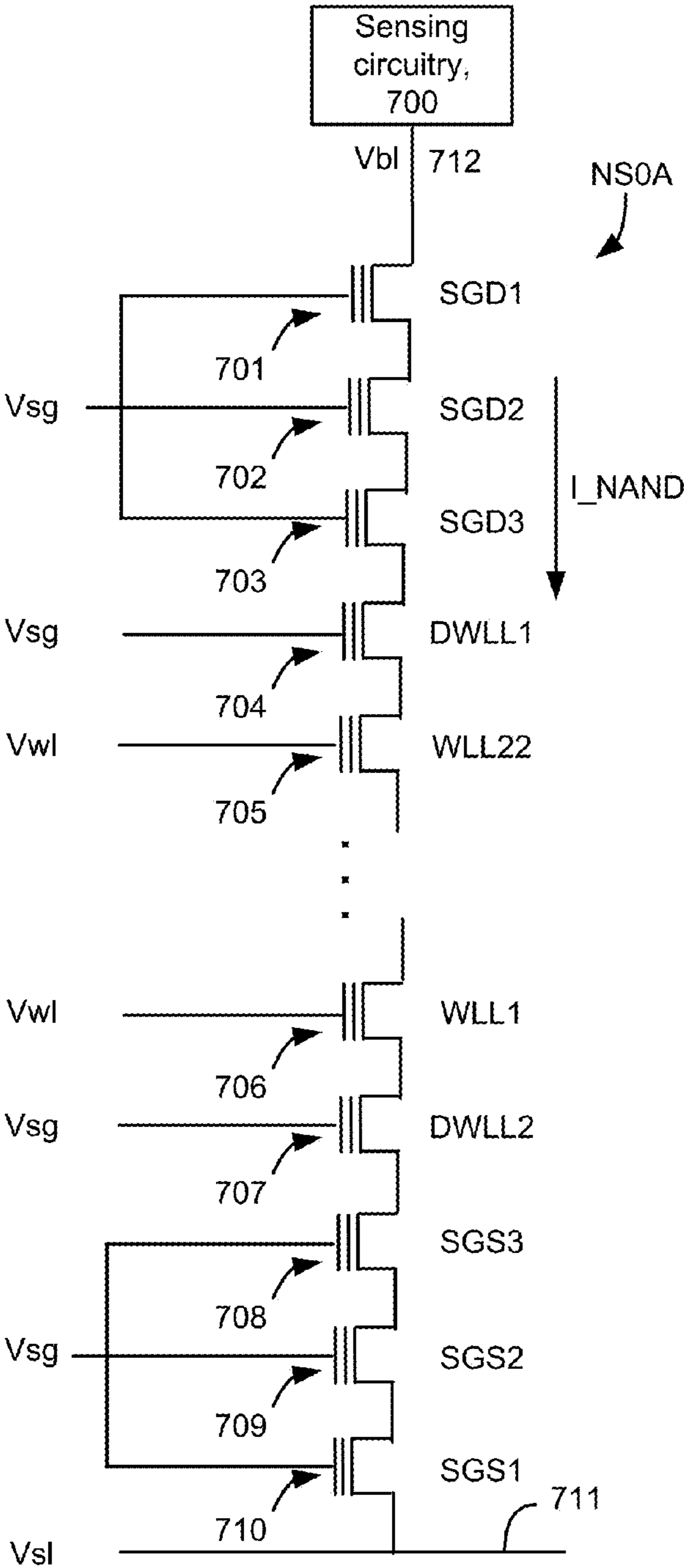


Fig. 7B

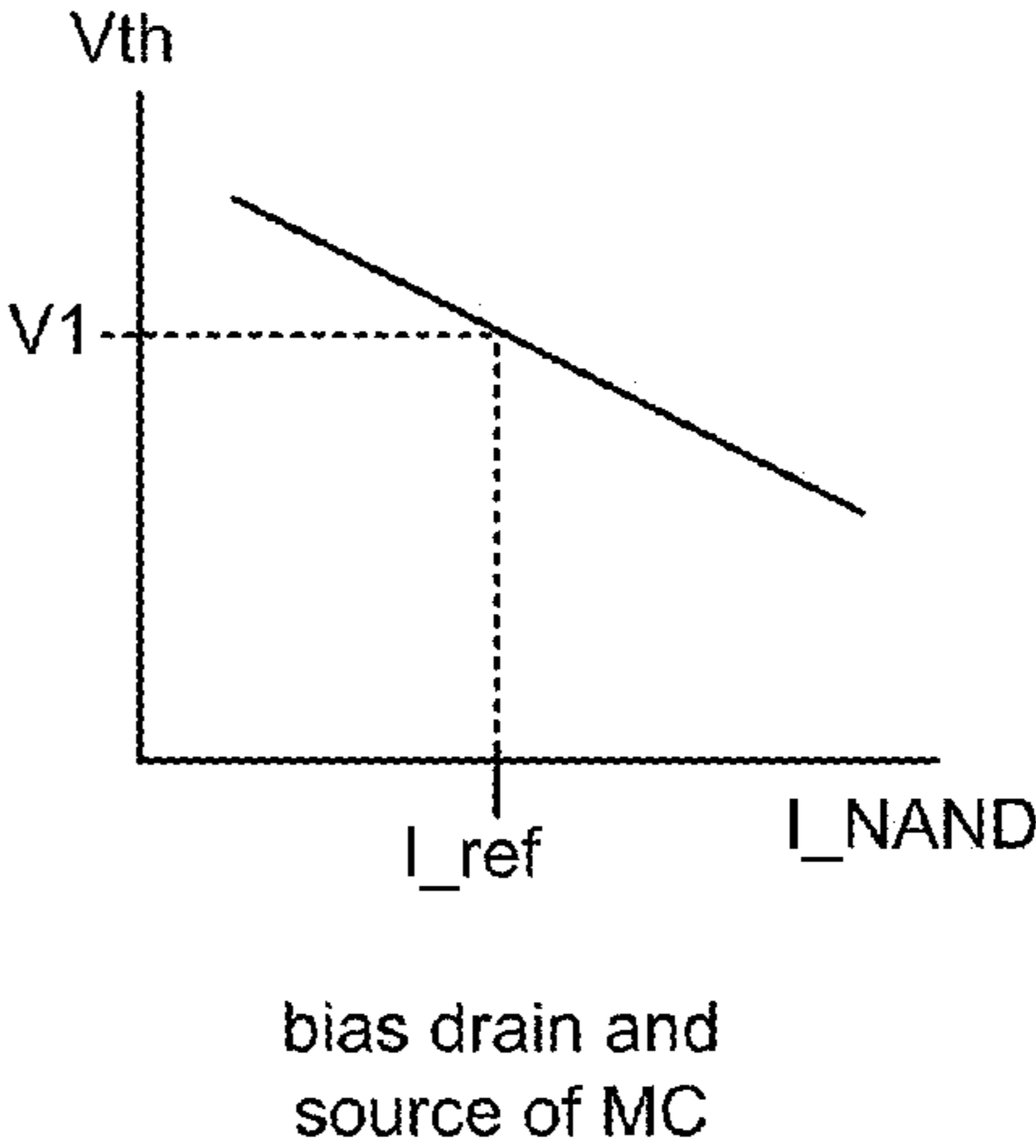


Fig. 8A

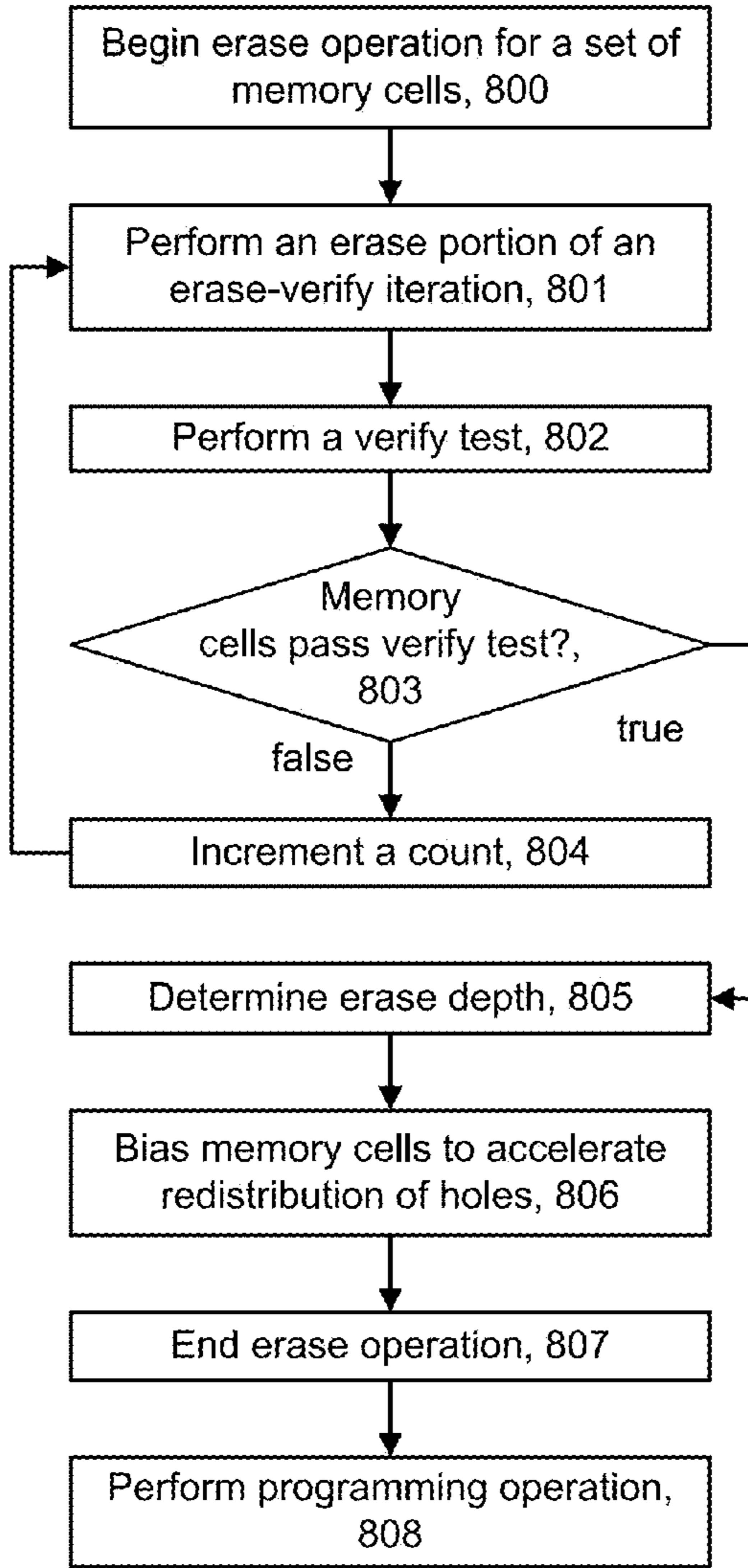


Fig. 8B

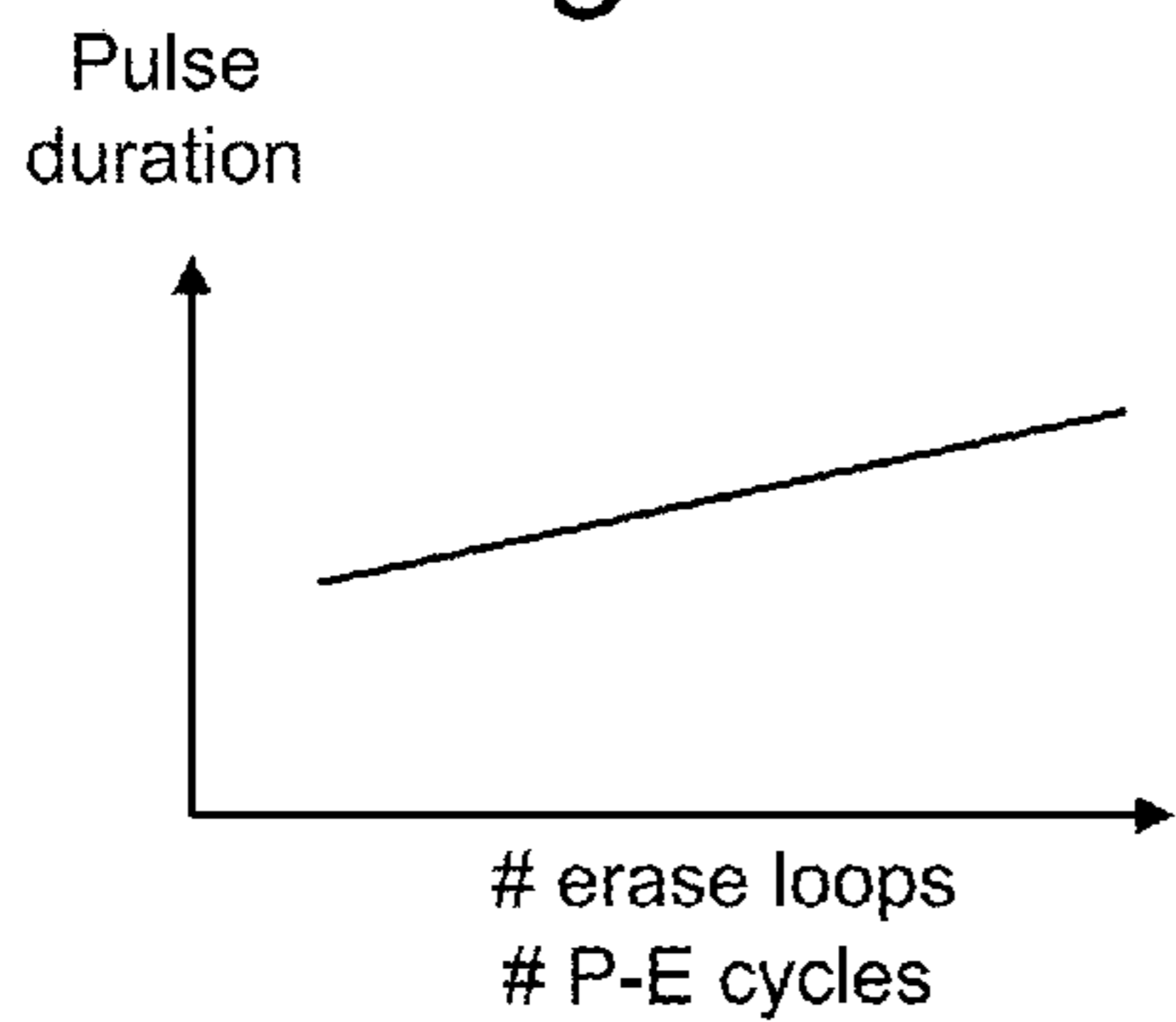


Fig. 8C

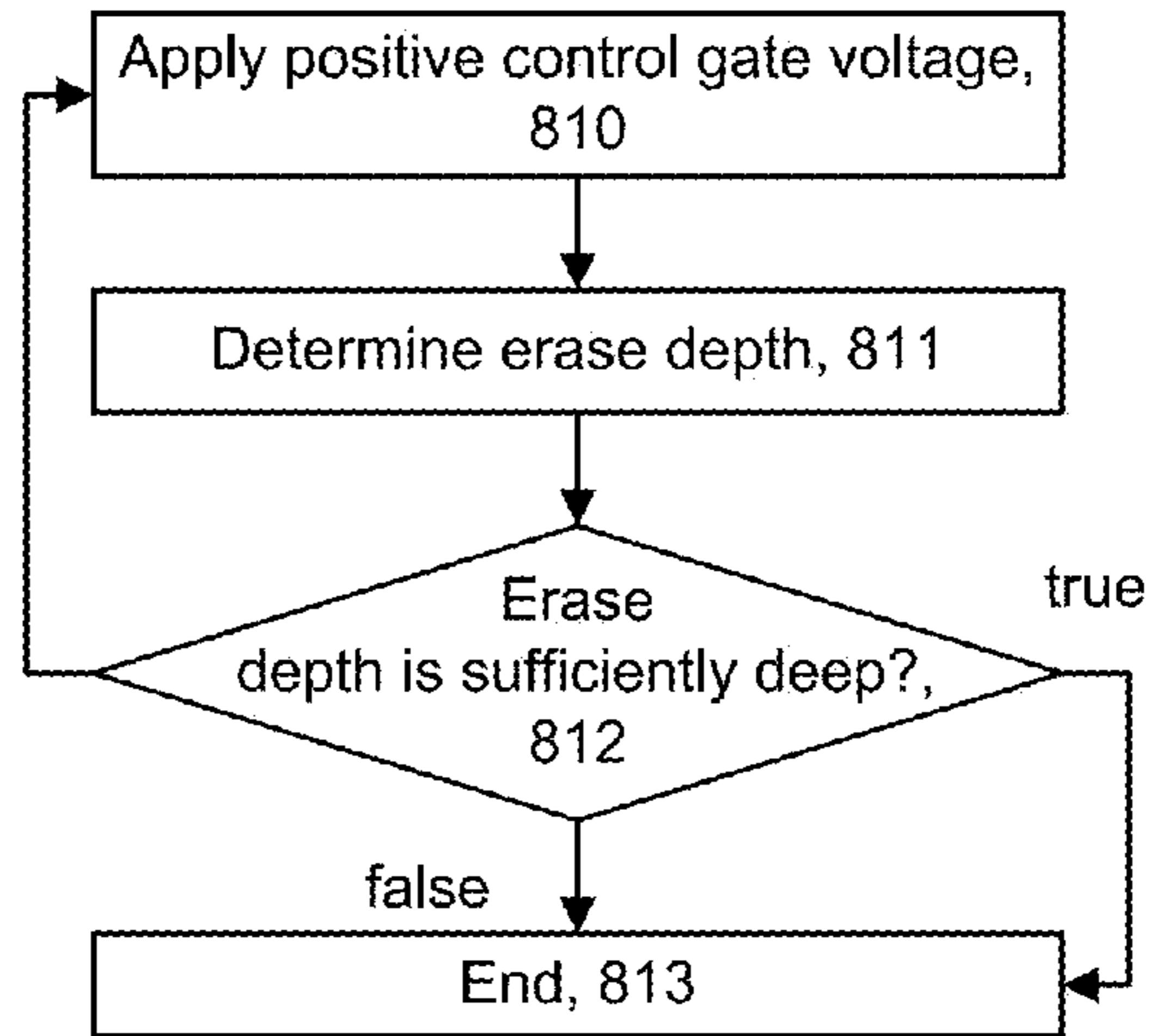
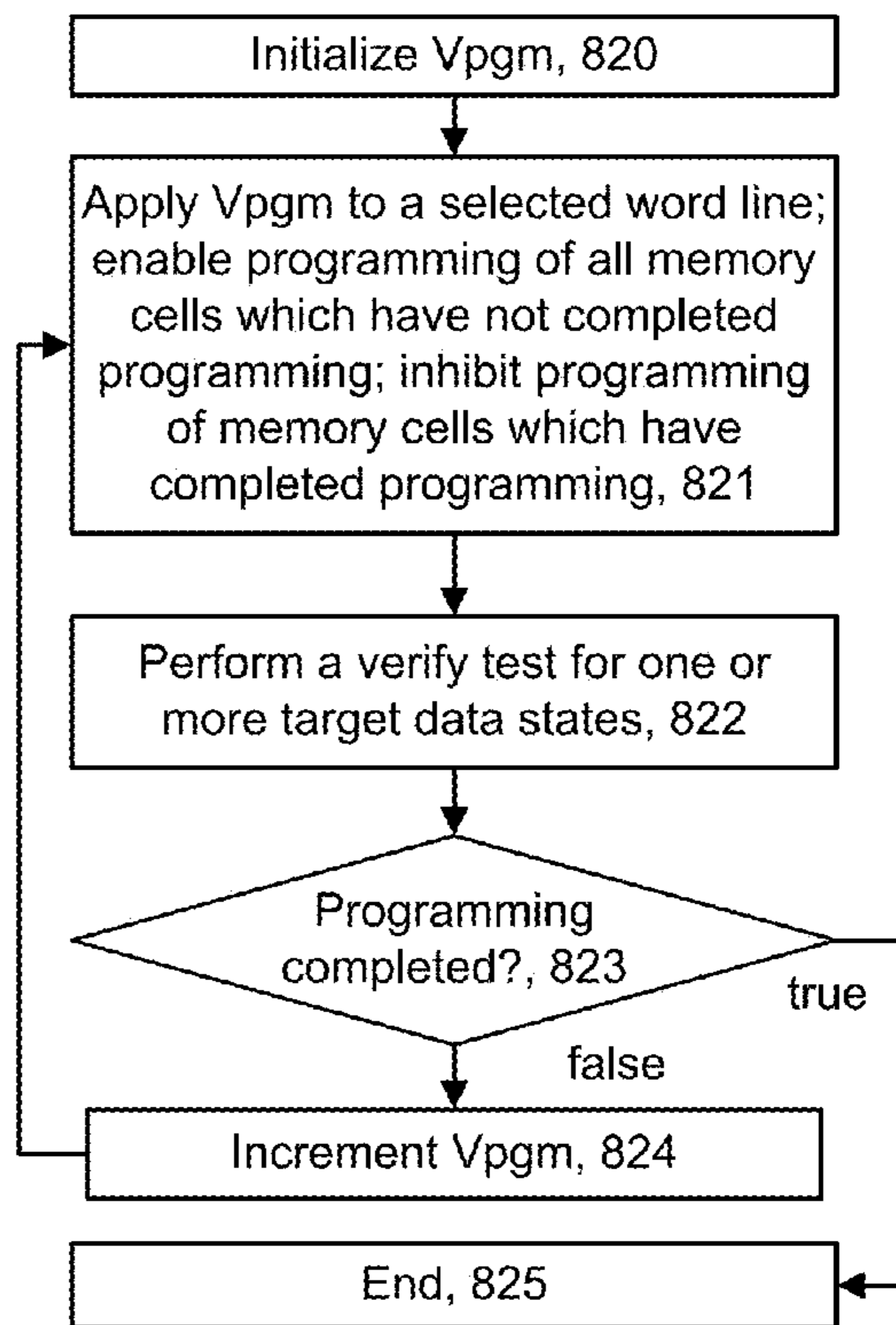


Fig. 8D



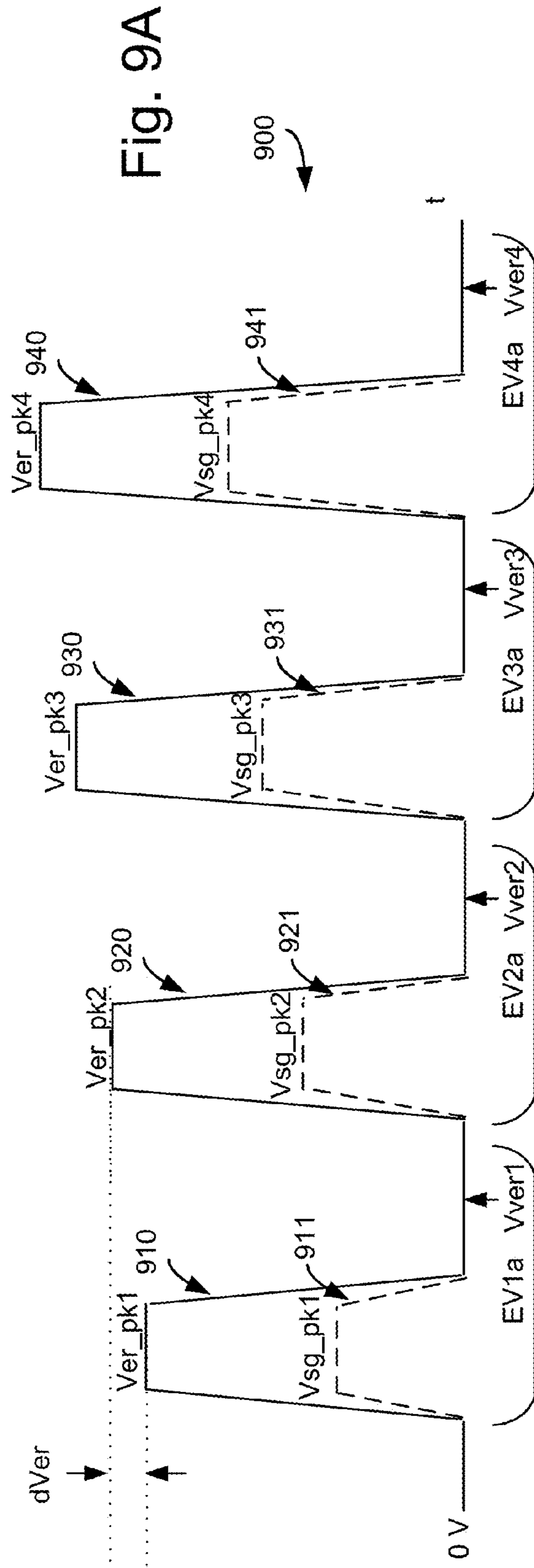


Fig. 9B

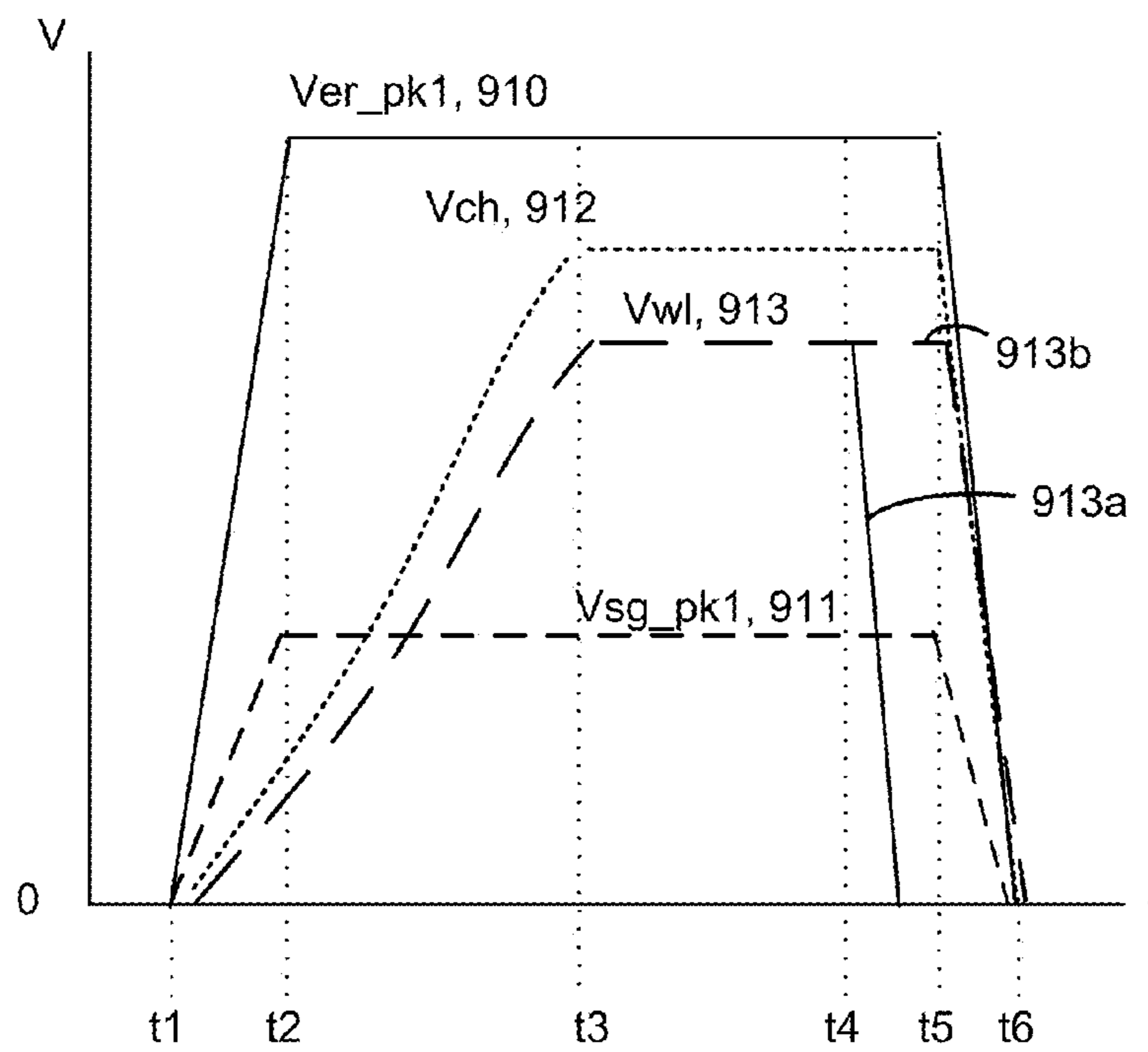
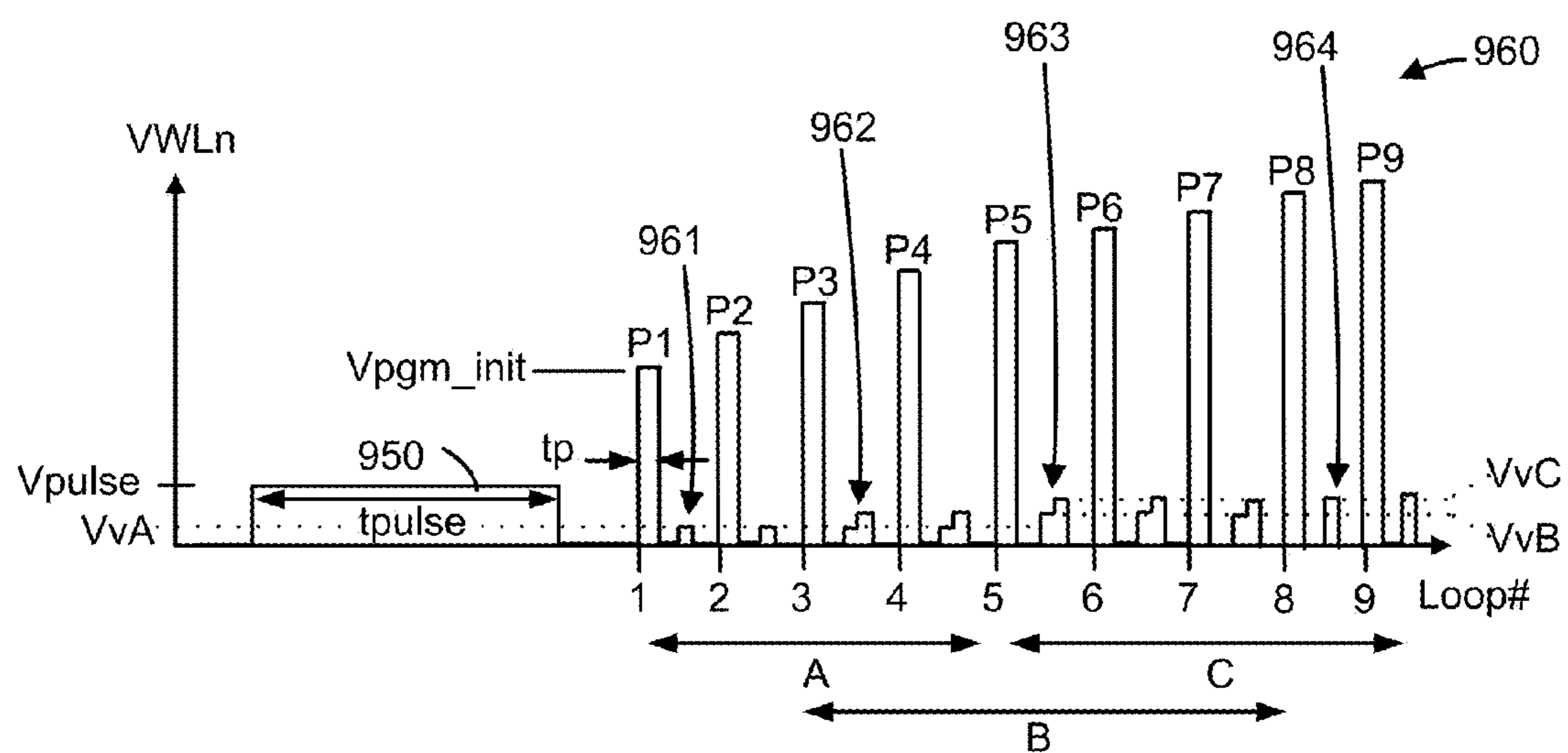


Fig. 9C



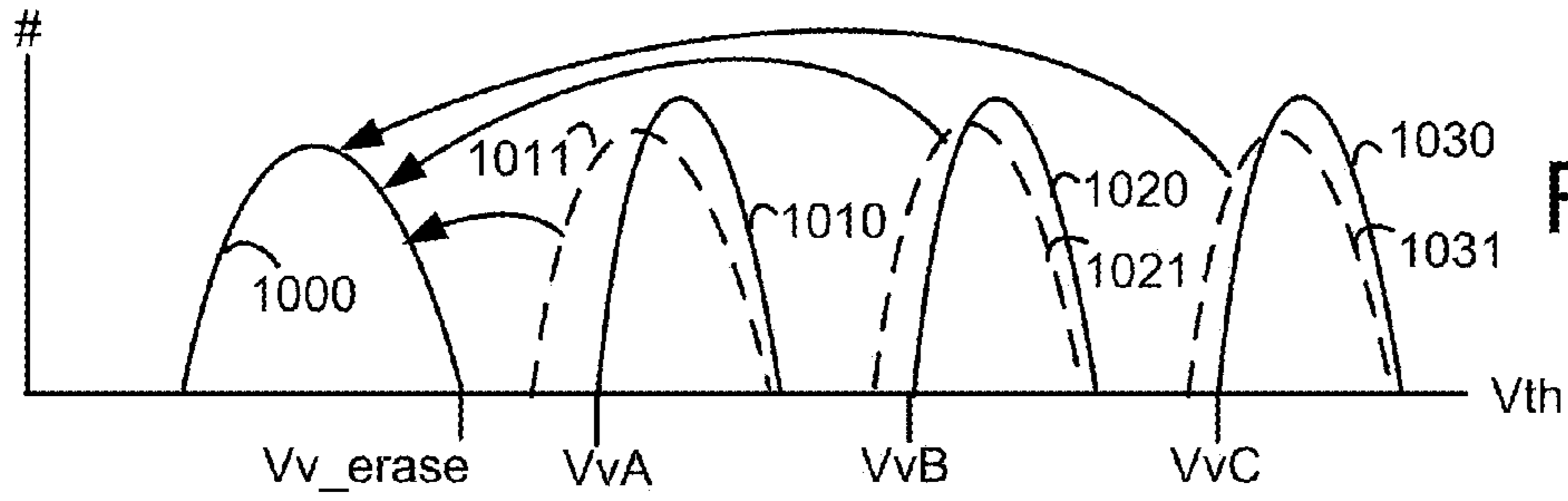


Fig. 10A

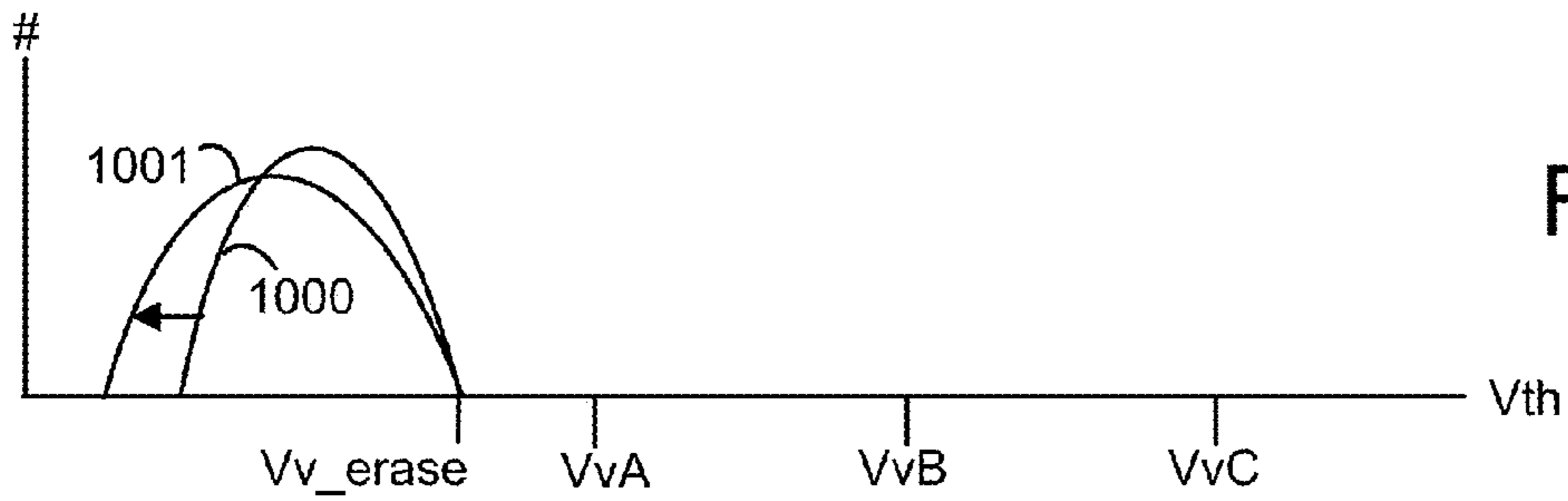


Fig. 10B

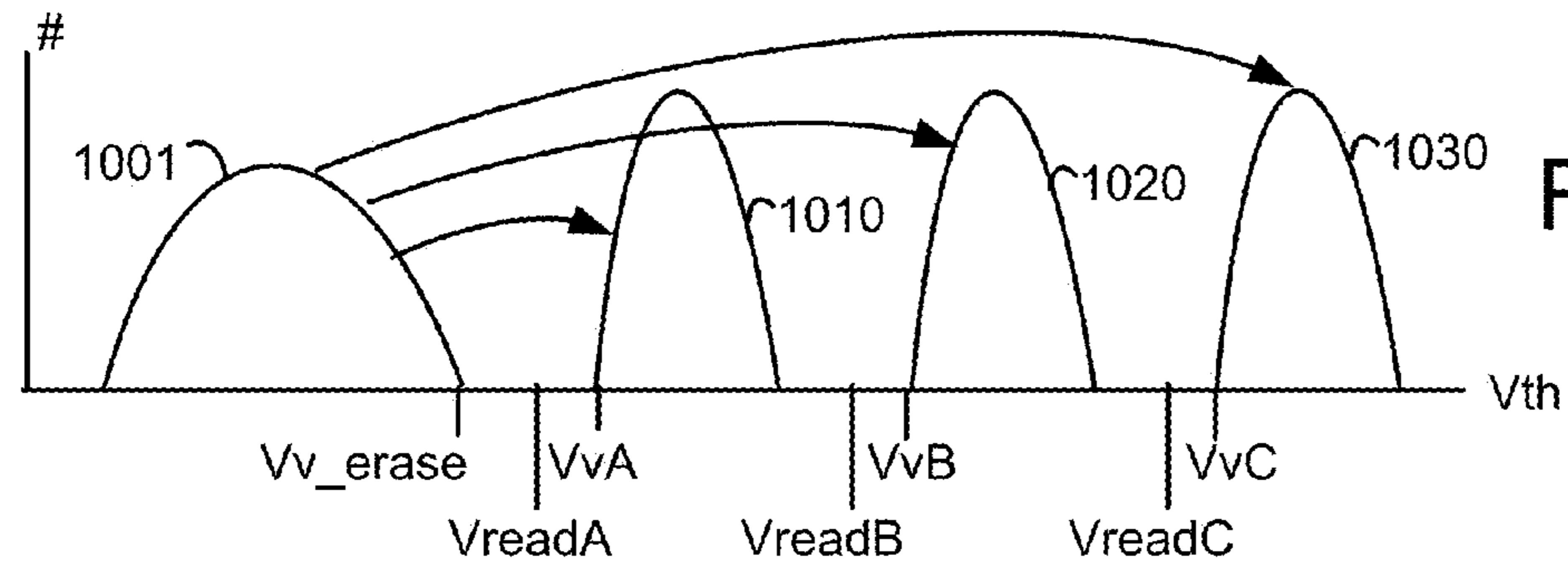


Fig. 10C

Fig. 10D

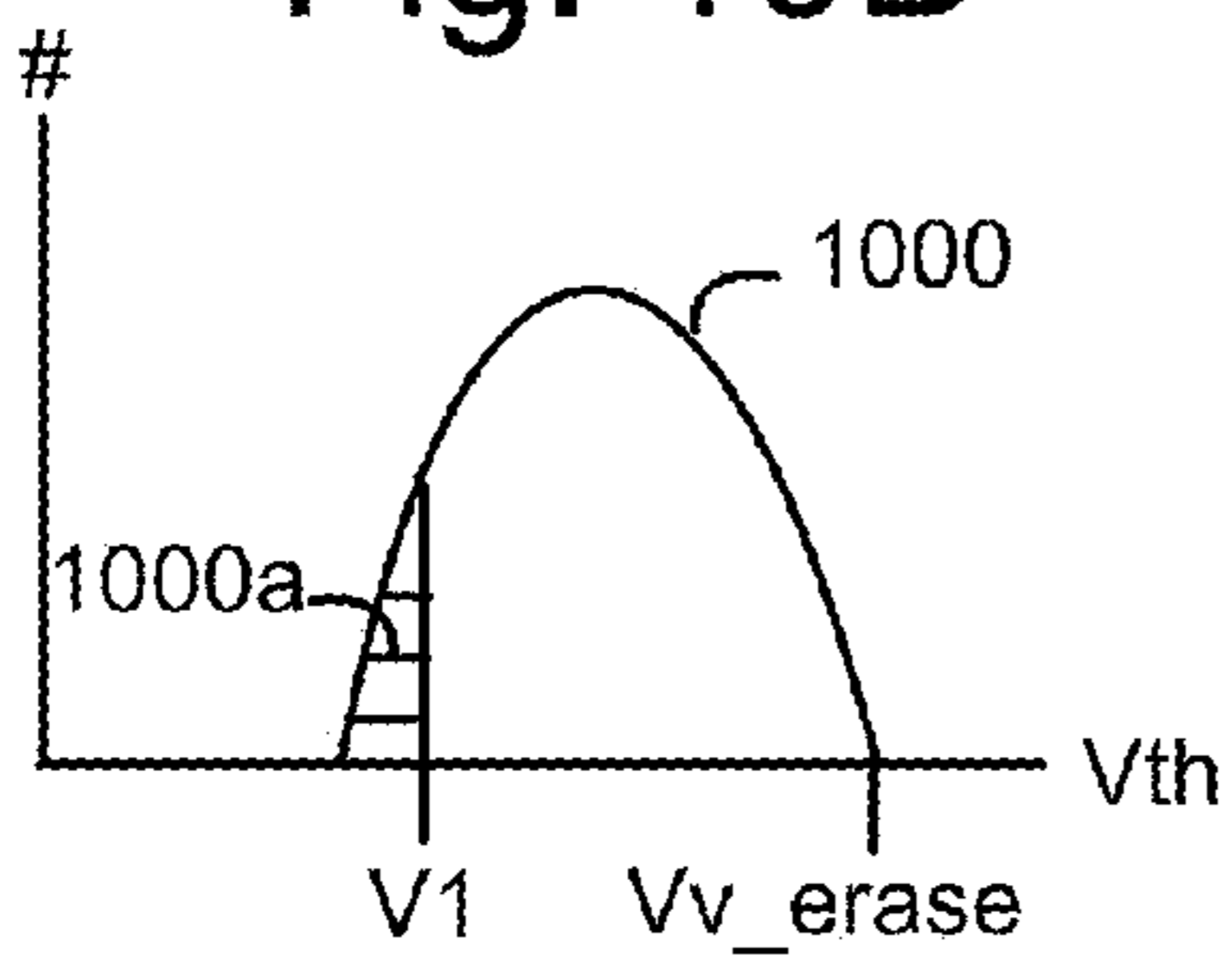


Fig. 10E

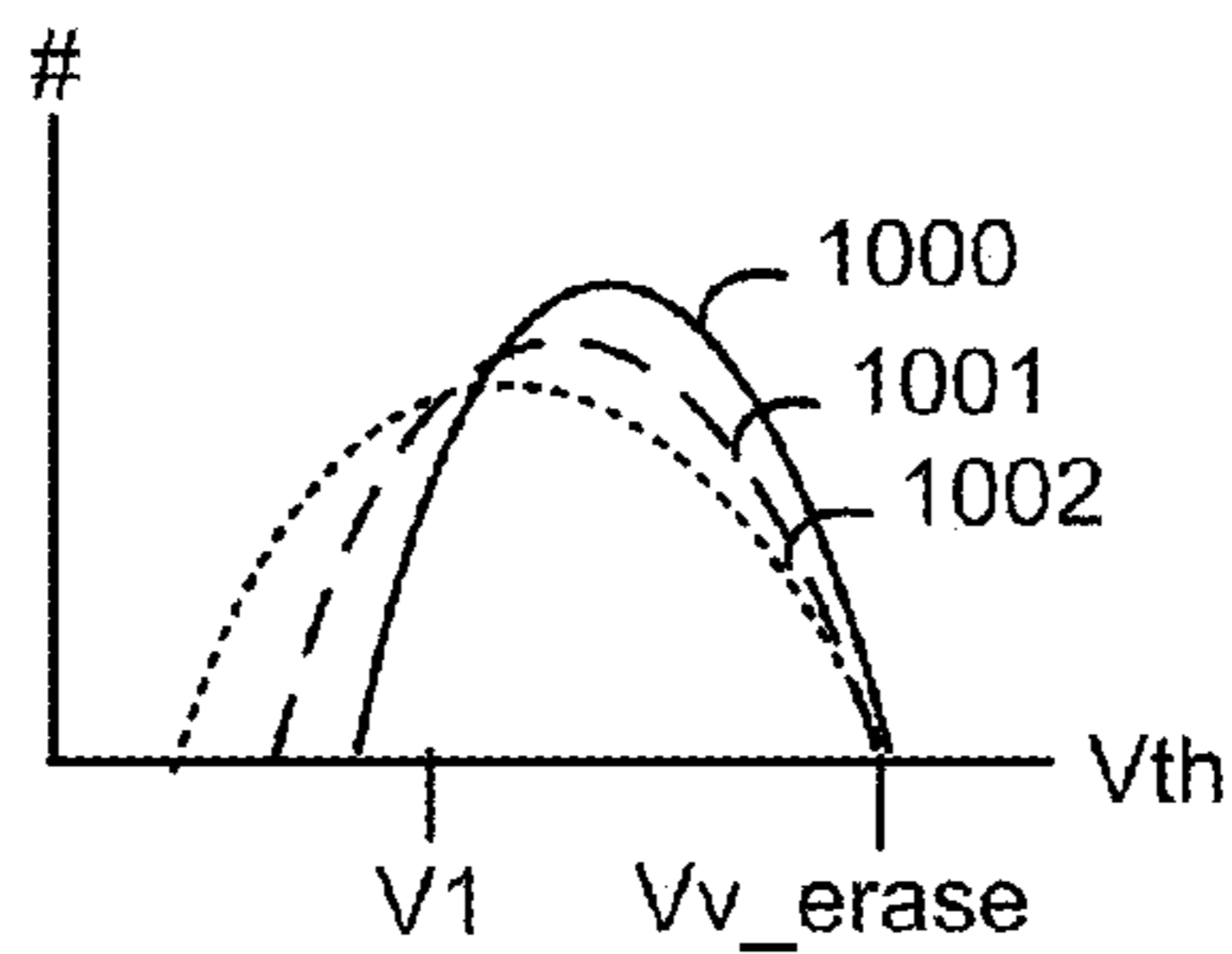
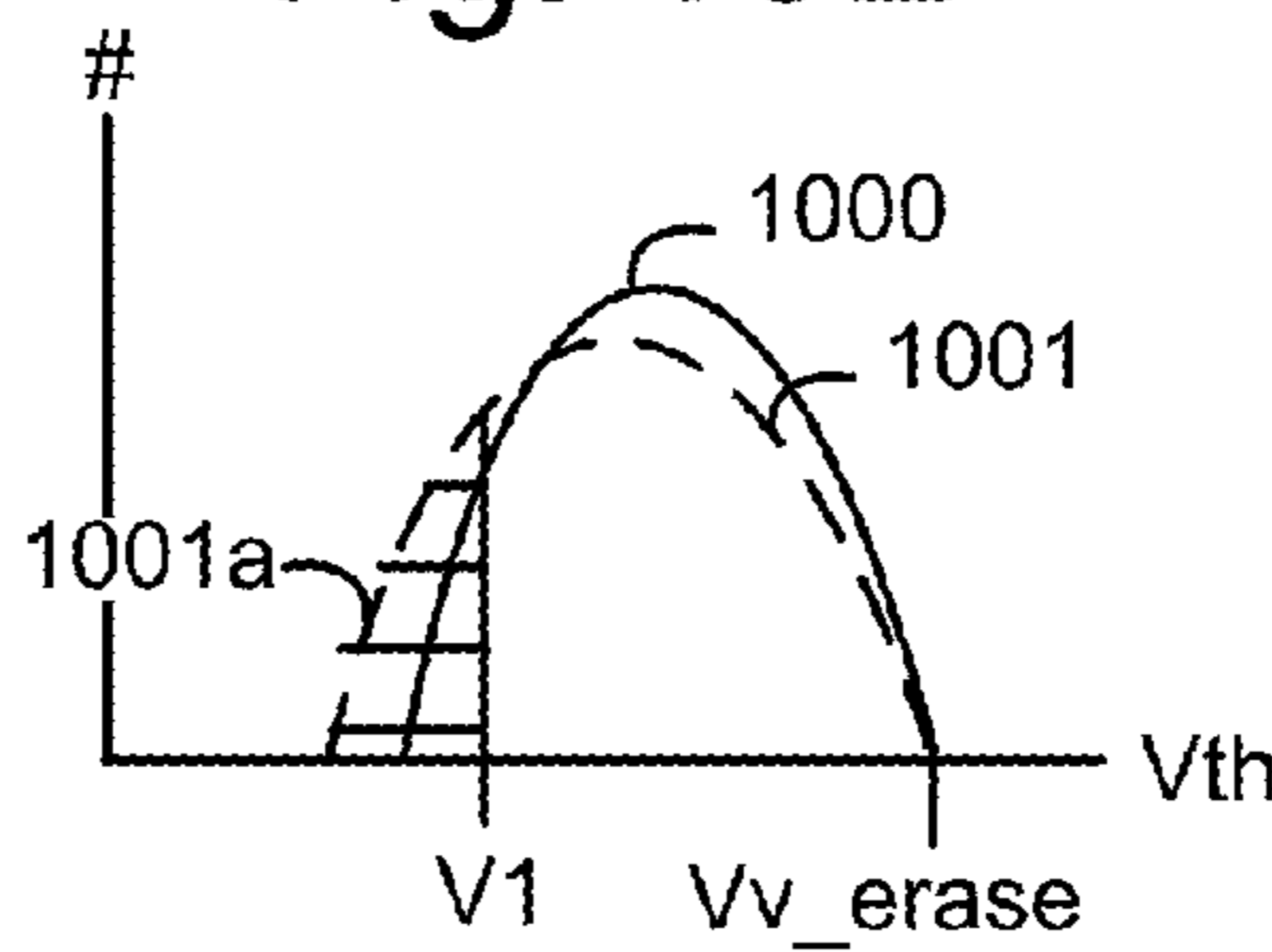


Fig. 10F

CHARGE REDISTRIBUTION DURING ERASE IN CHARGE TRAPPING MEMORY

BACKGROUND

The present technology relates to operation of memory devices.

A charge-trapping material can be used in memory devices to store a charge which represents a data state. The charge-trapping material can be arranged vertically in a three-dimensional (3D) stacked memory structure, or horizontally in a two-dimensional (2D) memory structure. One example of a 3D memory structure is the Bit Cost Scalable (BiCS) architecture which comprises a stack of alternating conductive and dielectric layers. A memory hole is formed in the stack and a NAND string is then formed by filling the memory hole with materials including a charge-trapping layer. A straight NAND string extends in one memory hole, while a pipe- or U-shaped NAND string (P—BiCS) includes a pair of vertical columns of memory cells which extend in two memory holes and which are joined by a bottom back gate. Control gates of the memory cells are provided by the conductive layers.

However, various challenges are presented in operating such memory devices.

BRIEF DESCRIPTION OF THE DRAWINGS

Like-numbered elements refer to common components in the different figures.

FIG. 1A is a perspective view of a 3D stacked non-volatile memory device.

FIG. 1B is a functional block diagram of a memory device such as the 3D stacked non-volatile memory device 100 of FIG. 1A.

FIG. 2A depicts a top view of example word line layers 202 and 204 in a U-shaped NAND embodiment, as an example implementation of BLK0 in FIG. 1A.

FIG. 2B depicts a top view of example select gate layer portions, consistent with FIG. 2A.

FIG. 2C depicts an embodiment of a stack 231 showing a cross-sectional view of the portion 209 of FIG. 2A, along line 220, where three select gate layers, SGL1, SGL2 and SGL3 are provided.

FIG. 3A depicts a top view of an example word line layer 304 of the block BLK0 of FIG. 1A, in a straight NAND string embodiment.

FIG. 3B depicts a top view of an example SGD layer 362, consistent with FIG. 3A.

FIG. 3C1 depicts an embodiment of a stack 376 showing a cross-sectional view of the portion 307 of FIG. 3A, along line 305, where three SGD layers, three SGS layers and dummy word line layers DWLL1 and DWLL2 are provided.

FIG. 3C2 depicts a variation in the width of a memory hole along its height.

FIG. 4A depicts a view of the region 246 of FIG. 3C1, showing SGD transistors D1a (consistent with FIG. 3C1), D1a1 and D1a2 above a dummy memory cell (DMC) and a data-storing memory cell (MC).

FIG. 4B depicts a cross-section view of the region 246 of FIG. 4A along line 444.

FIG. 4C depicts an expanded view of a portion of the SGD transistor D1a of FIG. 4A.

FIG. 4D depicts an expanded view of a region 410 of the NAND string of FIG. 3C2.

FIG. 5A depicts a cross-sectional view in a word line direction of memory cells comprising a flat control gate and

charge-trapping regions as a 2D example of memory cells in the memory structure 126 of FIG. 1B.

FIG. 5B depicts a cross sectional view along line 559 in FIG. 5A, showing a NAND string 530 having a flat control gate and a charge-trapping layer.

FIG. 5C depicts an expanded view of a portion 540 of the NAND string of FIG. 5B.

FIG. 6A is a plot of V_{th} versus time, showing a decrease in V_{th} after a memory cell is programmed due to short-term charge loss.

FIG. 6B depicts an energy band diagram for a charge-trapping memory cell.

FIG. 7A depicts a circuit diagram of a NAND string consistent with the memory devices of FIGS. 2C and 3C1.

FIG. 7B depicts a plot of V_{th} versus I_{NAND} , a current in a NAND string during a sensing operation.

FIG. 8A depicts an example erase operation in which the memory cells are biased to accelerate the redistribution of holes.

FIG. 8B depicts a plot showing an optimal pulse duration versus a number of erase loops or a number of program-erase (P-E) cycles, for use in step 805 of FIG. 8A.

FIG. 8C depicts an example process for implementing step 806 of FIG. 8A using multiple pulses.

FIG. 8D depicts an example programming operation, consistent with step 808 of FIG. 8A.

FIG. 9A depicts an example erase waveform 900 for use in step 801 of FIG. 8A.

FIG. 9B depicts a detailed view of the waveforms 910 and 911 of FIG. 9A in addition to a waveform 912 which represents a voltage of a channel of a NAND string, and a waveform 913 which represents a voltage of a control gate of a memory cell.

FIG. 9C depicts voltages applied to a word line in a programming operation, consistent with step 808 of FIG. 8A.

FIG. 10A depicts V_{th} distributions of a set of memory cells, showing a decrease in V_{th} due to charge loss, and a subsequent erase operation, consistent with steps 801 and 802 of FIG. 8A.

FIG. 10B depicts a decrease in the lower tail of the V_{th} distribution of the erased state due to biasing of memory cells to accelerate redistribution of holes, consistent with step 806 of FIG. 8A.

FIG. 10C depicts V_{th} distributions of a set of memory cells after programming, consistent with step 808 of FIG. 8A.

FIG. 10D depicts a portion of the V_{th} distribution of the erased state for which memory cells have a $V_{th} < V_1$, before biasing of memory cells to accelerate redistribution of holes, consistent with step 805 of FIG. 8A.

FIG. 10E depicts a portion of the V_{th} distribution of the erased state for which memory cells have a $V_{th} < V_1$, after biasing of memory cells to accelerate redistribution of holes, consistent with step 811 of FIG. 8C.

FIG. 10F depicts a decrease in the lower tail of the V_{th} distribution of the erased state in multiple steps, consistent with FIG. 8C.

DETAILED DESCRIPTION

Techniques are provided for reducing short-term charge loss in charge-trapping memory.

A charge-trapping memory device may use a charge-trapping material such as silicon nitride layer which is arranged between oxide layers (in an oxide-nitride-oxide or ONO configuration) next to a channel region. One example of a charge-trapping memory device is a 3D memory device in which a stack of alternating conductive and dielectric layers are

formed. Memory holes are etched in the stack and films are deposited in the holes such that memory cells or select gate transistors are formed where the conductive layers intersect with the memory holes. The films include a charge-trapping layer which extends vertically along an individual cell or an entire NAND string. Some of the conductive layers are used as control gates for memory cells and other conductive layers are used as control gates for select gate transistors, such as drain or source side transistors in NAND strings. Another example of a charge-trapping memory device is a 2D memory device in which the charge-trapping layer extends horizontally along a NAND string.

During programming of a charge-trapping memory cell, electrons move from the channel to the nitride layer. However, a short-term charge loss occurs due to fast charge detrapping from shallow traps in the ONO layers into the channel. This can occur a few seconds or minutes after a memory cell has completed programming to a target data state according to a verify test. As a result of the charge loss, the threshold voltage (V_{th}) of the memory cell can decrease to the point where the target data state cannot be accurately read back from the memory cell. Generally, the charge loss causes a set of cells to have a widened V_{th} distribution which has downshifted below the verify voltages. This is in conflict with the need to provide narrow V_{th} distributions to allow multiple data states to be stored.

Short-term charge loss is believed to be caused by holes which are trapped in the upper portion of the charge-trapping material, which is a portion of the charge-trapping material which is furthest from the channel. After programming, the holes are thermally activated to the valence band and diffuse away to the lower portion of the charge-trapping material, which is a portion of the charge-trapping material which is closest to the channel, thereby lowering the V_{th} . Thus, there is a redistribution of the holes in the charge-trapping material which results in a lowering of the V_{th} .

Techniques provided herein accelerate the redistribution of the holes in connection with an erase operation, so that there will be a reduced amount of redistribution of the holes after programming. As a result, short-term charge loss after programming is reduced. In one aspect, the techniques include applying a positive control gate voltage to a set of memory cells after a plurality of erase-verify iterations have been performed and before a programming operation begins. The positive control gate voltage has a relatively low amplitude and a long duration, compared to a programming voltage. The positive control gate voltage provides an electron flux in the charge-trapping material which recombines with the holes and mitigates the subsequent hole redistribution in the charge-trapping material after programming. Since the holes are redistributed while the memory cells are in the erased state, the lower tail of the V_{th} distribution of the erased state will decrease. This is in contrast to soft programming which seeks to narrow the V_{th} distribution of the erased state by raising the lower tail. The positive control gate voltage should therefore have a magnitude and duration which is sufficiently low to avoid programming of the memory cells above the erased state, and which is sufficiently high to accelerate the redistribution of holes in the charge-trapping material.

In another aspect, the positive control gate voltage is adjusted based on the erase depth of the memory cells. The positive control gate voltage has a duration which is relatively longer when the erase depth is relatively deeper. The erase depth is proportional to how negative the lower tail is in the V_{th} distribution of the erased state. Generally, the erase depth is deeper when a count of program-erase cycles in the memory device is relatively greater, since the memory cells

become easier to erase (and program) as program-erase cycles accumulate. Thus, the positive control gate voltage has a duration which is relatively shorter when a count of program-erase cycles in the memory device is relatively lower.

Moreover, the erase depth is deeper when a count of erase-verify iterations is relatively greater. Thus, the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

In another aspect, a position of the lower tail of the V_{th} distribution is sensed, and the positive control gate voltage is adjusted accordingly. For example, the positive control gate voltage has a duration which is relatively shorter when the position is relatively higher.

In another aspect, a position of the lower tail is sensed after a first positive control gate voltage is applied, and a decision is made to apply a second positive control gate voltage if the lower tail is not sufficiently low.

In another aspect, the positive control gate voltage has a duration which is a function of a height of a selected word line in the memory device. The duration is relatively shorter when the height is associated with a relatively smaller cross-sectional width of a vertical pillar of a memory hole.

The following discussion provides details of the construction of example memory devices and of related techniques which address the above and other issues.

FIG. 1A is a perspective view of a 3D stacked non-volatile memory device. The memory device **100** includes a substrate **101**. On the substrate are example blocks **BLK0** and **BLK1** of memory cells and a peripheral area **104** with circuitry for use by the blocks. The substrate **101** can also carry circuitry under the blocks, along with one or more lower metal layers which are patterned in conductive paths to carry signals of the circuitry. The blocks are formed in an intermediate region **102** of the memory device. In an upper region **103** of the memory device, one or more upper metal layers are patterned in conductive paths to carry signals of the circuitry. Each block comprises a stacked area of memory cells, where alternating levels of the stack represent word lines. In one possible approach, each block has opposing tiered sides from which vertical contacts extend upward to an upper metal layer to form connections to conductive paths. While two blocks are depicted as an example, additional blocks can be used, extending in the x- and/or y-directions.

In one possible approach, the length of the plane, in the x-direction, represents a direction in which signal paths to word lines extend in the one or more upper metal layers (a word line or SGD line direction), and the width of the plane, in the y-direction, represents a direction in which signal paths to bit lines extend in the one or more upper metal layers (a bit line direction). The z-direction represents a height of the memory device.

FIG. 1B is a functional block diagram of a memory device such as the 3D stacked non-volatile memory device **100** of FIG. 1A. The memory device **100** may include one or more memory die **108**. The memory die **108** includes a memory structure **126** of memory cells, such as an array of cells, control circuitry **110**, and read/write circuits **128**. In a 3D configuration, the memory structure can include the blocks **BLK0** and **BLK1** of FIG. 1A. The memory structure **126** is addressable by word lines via a row decoder **124** and by bit lines via a column decoder **132**. The read/write circuits **128** include multiple sense blocks **130** (sensing circuitry) and allow a page of memory cells to be read or programmed in parallel. Typically a controller **122** is included in the same memory device **100** (e.g., a removable storage card) as the one or more memory die **108**. Commands and data are trans-

ferred between the host and controller **122** via lines **120** and between the controller and the one or more memory die **108** via lines **118**.

The memory structure may comprise one or more array of memory cells including a 3D array. The memory structure may comprise a monolithic three dimensional memory structure in which multiple memory levels are formed above (and not in) a single substrate, such as a wafer, with no intervening substrates. The memory structure may comprise any type of non-volatile memory that is monolithically formed in one or more physical levels of arrays of memory cells having an active area disposed above a silicon substrate. The memory structure may be in a non-volatile memory device having circuitry associated with the operation of the memory cells, whether the associated circuitry is above or within the substrate.

The control circuitry **110** cooperates with the read/write circuits **128** to perform memory operations on the memory structure **126**, and includes a state machine **112**, an on-chip address decoder **114**, and a power control module **116**. The state machine **112** provides chip-level control of memory operations. A storage region **115** may be provided for a count of program-erase cycles in the memory device.

The on-chip address decoder **114** provides an address interface between that used by the host or a memory controller to the hardware address used by the decoders **124** and **132**. The power control module **116** controls the power and voltages supplied to the word lines and bit lines during memory operations. It can include drivers for word line layers (WLLs) in a 3D configuration, SGS and SGD transistors and source lines. The sense blocks **130** can include bit line drivers, in one approach. An SGS transistor is a select gate transistor at a source end of a NAND string, and an SGD transistor is a select gate transistor at a drain end of a NAND string.

In some implementations, some of the components can be combined. In various designs, one or more of the components (alone or in combination), other than memory structure **126**, can be thought of as at least one control circuit which is configured to perform the actions described herein. For example, a control circuit may include any one of, or a combination of, control circuitry **110**, state machine **112**, decoders **114/132**, power control module **116**, sense blocks **130**, read/write circuits **128**, and controller **122**, and so forth.

Other types of non-volatile memory in addition to NAND flash memory can also be used.

Semiconductor memory devices include volatile memory devices, such as dynamic random access memory (“DRAM”) or static random access memory (“SRAM”) devices, non-volatile memory devices, such as resistive random access memory (“ReRAM”), electrically erasable programmable read only memory (“EEPROM”), flash memory (which can also be considered a subset of EEPROM), ferroelectric random access memory (“FRAM”), and magnetoresistive random access memory (“MRAM”), and other semiconductor elements capable of storing information. Each type of memory device may have different configurations. For example, flash memory devices may be configured in a NAND or a NOR configuration.

The memory devices can be formed from passive and/or active elements, in any combinations. By way of non-limiting example, passive semiconductor memory elements include ReRAM device elements, which in some embodiments include a resistivity switching storage element, such as an anti-fuse or phase change material, and optionally a steering element, such as a diode or transistor. Further by way of non-limiting example, active semiconductor memory elements include EEPROM and flash memory device elements,

which in some embodiments include elements containing a charge storage region, such as a floating gate, conductive nanoparticles, or a charge storage dielectric material.

Multiple memory elements may be configured so that they are connected in series or so that each element is individually accessible. By way of non-limiting example, flash memory devices in a NAND configuration (NAND memory) typically contain memory elements connected in series. A NAND string is an example of a set of series-connected transistors comprising memory cells and select gate transistors.

A NAND memory array may be configured so that the array is composed of multiple strings of memory in which a string is composed of multiple memory elements sharing a single bit line and accessed as a group. Alternatively, memory elements may be configured so that each element is individually accessible, e.g., a NOR memory array. NAND and NOR memory configurations are exemplary, and memory elements may be otherwise configured.

The semiconductor memory elements located within and/or over a substrate may be arranged in two or three dimensions, such as a two dimensional memory structure or a three dimensional memory structure.

In a two dimensional memory structure, the semiconductor memory elements are arranged in a single plane or a single memory device level. Typically, in a two dimensional memory structure, memory elements are arranged in a plane (e.g., in a direction plane) which extends substantially parallel to a major surface of a substrate that supports the memory elements. The substrate may be a wafer over or in which the layer of the memory elements are formed or it may be a carrier substrate which is attached to the memory elements after they are formed. As a non-limiting example, the substrate may include a semiconductor such as silicon.

The memory elements may be arranged in the single memory device level in an ordered array, such as in a plurality of rows and/or columns. However, the memory elements may be arrayed in non-regular or non-orthogonal configurations. The memory elements may each have two or more electrodes or contact lines, such as bit lines and word lines.

A three dimensional memory array is arranged so that memory elements occupy multiple planes or multiple memory device levels, thereby forming a structure in three dimensions (i.e., in the x, y and z directions, where the z direction is substantially perpendicular and the x and y directions are substantially parallel to the major surface of the substrate).

As a non-limiting example, a three dimensional memory structure may be vertically arranged as a stack of multiple two dimensional memory device levels. As another non-limiting example, a three dimensional memory array may be arranged as multiple vertical columns (e.g., columns extending substantially perpendicular to the major surface of the substrate, i.e., in the y direction) with each column having multiple memory elements. The columns may be arranged in a two dimensional configuration, e.g., in an plane, resulting in a three dimensional arrangement of memory elements with elements on multiple vertically stacked memory planes. Other configurations of memory elements in three dimensions can also constitute a three dimensional memory array.

By way of non-limiting example, in a three dimensional NAND memory array, the memory elements may be coupled together to form a NAND string within a single horizontal (e.g., x-y) memory device level. Alternatively, the memory elements may be coupled together to form a vertical NAND string that traverses across multiple horizontal memory device levels. Other three dimensional configurations can be envisioned wherein some NAND strings contain memory

elements in a single memory level while other strings contain memory elements which span through multiple memory levels. Three dimensional memory arrays may also be designed in a NOR configuration and in a ReRAM configuration.

Typically, in a monolithic three dimensional memory array, one or more memory device levels are formed above a single substrate. Optionally, the monolithic three dimensional memory array may also have one or more memory layers at least partially within the single substrate. As a non-limiting example, the substrate may include a semiconductor such as silicon. In a monolithic three dimensional array, the layers constituting each memory device level of the array are typically formed on the layers of the underlying memory device levels of the array. However, layers of adjacent memory device levels of a monolithic three dimensional memory array may be shared or have intervening layers between memory device levels.

Then again, two dimensional arrays may be formed separately and then packaged together to form a non-monolithic memory device having multiple layers of memory. For example, non-monolithic stacked memories can be constructed by forming memory levels on separate substrates and then stacking the memory levels atop each other. The substrates may be thinned or removed from the memory device levels before stacking, but as the memory device levels are initially formed over separate substrates, the resulting memory arrays are not monolithic three dimensional memory arrays. Further, multiple two dimensional memory arrays or three dimensional memory arrays (monolithic or non-monolithic) may be formed on separate chips and then packaged together to form a stacked-chip memory device.

Associated circuitry is typically required for operation of the memory elements and for communication with the memory elements. As non-limiting examples, memory devices may have circuitry used for controlling and driving memory elements to accomplish functions such as programming and reading. This associated circuitry may be on the same substrate as the memory elements and/or on a separate substrate. For example, a controller for memory read-write operations may be located on a separate controller chip and/or on the same substrate as the memory elements.

One of skill in the art will recognize that this technology is not limited to the two dimensional and three dimensional exemplary structures described but covers all relevant memory structures within the spirit and scope of the technology as described herein and as understood by one of skill in the art.

FIG. 2A depicts a top view of example word line layers **202** and **204** in a U-shaped NAND embodiment, as an example implementation of **BLK0** in FIG. 1A. In a 3D stacked memory device, memory cells are formed along memory holes which extend through alternating conductive and dielectric layers in a stack. The memory cells are typically arranged in NAND strings. Each conductive layer can include one or more word line layers. A word line layer is an example of a word line.

The view is of a representative layer among the multiple WLLs in a stack. Referring also to FIG. 2C, the stack includes alternating dielectric and conductive layers. The dielectric layers include **DL0** to **DL25** and may be made of SiO_2 , for instance. The conductive layers include a back gate layer (BGL), data-storing word line layers **WLL0** to **WLL19**, dummy (non-data-storing) word line layers **DWLLa** and **DWLLb**, and select gate layers **SGL1**, **SGL2** and **SGL3**. The word line layers are conductive paths to control gates of the memory cells at the layer. Moreover, each select gate layer

may comprises conductive lines to select gate transistors (e.g., SGD and/or SGS transistors).

The word line layers of FIG. 2A may represent any one of the word line layers in FIG. 2C. These conductive layers may include doped polysilicon, metal such as tungsten or metal silicide, for instance. An example voltage of 5-10 V may be applied to the back gate to maintain a conductive state which connects the drain- and source-side columns.

For each block, each conductive layer may be divided into two word line layers **202** and **204** which are insulated from one another by a slit **206**. The slit is formed by etching a void which extends vertically in the stack, typically from an etch stop layer at the bottom to at least a top layer of the stack, then filling the slit with insulation. This is an example of the type of etching which can result in the accumulation of charges in the top conductive layer of the stack. The slit **206** is a single continuous slit which extends in a zig-zag pattern in the block. This approach can provide greater flexibility in controlling the memory cells since the WLLs can be driven independently.

Each block includes memory holes or pillars which extend vertically in the stack, and comprise a column of memory cells such as in a NAND string. Each circle represents a memory hole or a memory cell associated with the word line layer. Example columns of memory cells along a line **220** include **C0** to **C11**. Columns **C0**, **C3**, **C4**, **C7**, **C8** and **C11** represent the drain side columns of respective NAND strings. Columns **C1**, **C2**, **C5**, **C6**, **C9** and **C10** represent the source side columns of respective NAND strings. The figure represents a simplification, as many more rows of memory holes will typically be used, extending to the right and left in the figure. Also, the figures are not necessarily to scale. The columns of memory cells can be arranged in subsets such as sub-blocks.

Further, the NAND strings are arranged in sets, where each NAND string in a set has an SGD transistor with a common control gate voltage. See also FIG. 2B. Regions **201**, **203**, **205**, **207**, **208** and **210** each represent a set of NAND strings, or a set of memory cells in a word line layer. For example, region **210** includes NAND strings **NS0**, . . . , **NS0-14**. A programming operation can involve one set of NAND strings. Each NAND string in a set can be associated with a respective bit line which is independently controlled to allow or inhibit programming.

The drawings are not to scale and do not show all memory columns. For example, a more realistic block might have twelve memory columns in the y direction as shown, but a very large number such as 32 k memory columns in the x direction, for a total of 384,000 memory columns in a block. With U-shaped NAND strings, 192 k NAND strings are provided in this example. With straight NAND strings, 384,000 NAND strings are provided in this example. Assuming there are twenty-four memory cells per column, there are $384,000 \times 24 = 9,216,000$ memory cells in the set.

FIG. 2B depicts a top view of example select gate layer portions, consistent with FIG. 2A. In one approach, the select gate layer **215** is different than a WLL in that a separate SGD layer portion or line, is provided for each set of NAND strings. That is, each single row of SGD transistors extending in the x direction is separately controlled. In other words, the control gates of the SGD transistors in each set of NAND strings are commonly controlled.

Further, an SGS layer portion or line is provided for a pair of rows of SGS transistors extending in the x direction, in one approach, for adjacent sets of NAND strings. Optionally, additional slits are used so that a separate SGS layer portion is provided for a single row of SGS transistors extending in the

x direction. Thus, the control gates of the SGS transistors in a pair of rows of SGS transistors, or in a single row of SGS transistors, are also commonly controlled.

The SGS and SGD layer portions are created due to slits **239, 240, 241, 242, 243, 245, 247** and **248**. The slits extend partway down in the stack as depicted by example slit **241** in FIG. 2C. Regions **227, 228, 229, 232, 233** and **237** represent SGD transistors in SGD layer portions **216, 218, 219, 223, 224** and **226**, respectively. Regions **253** and **254, 255** and **257, 258** and **259** represent SGS transistors in SGS layer portions **217, 221** and **225**, respectively. Regions **255** and **257, 258** and **259**, represent SGS transistors in SGS layer portions **221** and **225**, respectively. The portion **209** from FIG. 2A is repeated for reference.

The select gate transistors are associated with NAND strings NS0-NS5.

FIG. 2C depicts an embodiment of a stack **231** showing a cross-sectional view of the portion **209** of FIG. 2A, along line **220**, where three select gate layers, SGL1, SGL2 and SGL3 are provided. In this case, the slit extends down to DL22, so that three separate layers of select gate transistors are formed in each column of each NAND string. The stack has a top **287** and a bottom **238**.

The conductive layers of the select gates can have a same height (channel length) as the conductive layers of the memory cells, in one approach. This facilitates the fabrication of the memory device. In a column, the individual select gate transistors together are equivalent to one select gate transistor having a channel length which is the sum of the channel lengths of the individual select gate transistors. Further, in one approach, select gate transistors in a column (e.g., in layers SGL1, SGL2 and SGL3) are connected and received a common voltage during operations. The SGS transistors can have a similar construction as the SGD transistors. Further, the SGS and SGD transistors can have a similar construction as the memory cell transistors.

The substrate may be p-type and can provide a ground which is connected to the top select gate layer, in one approach. A via **244** connects a drain side of C0 and NS0 to a bit line **288**. A via **262** connects a source side of C1 and NS0 to a source line **289**. Back gates **263, 264, 265** and **266** are provided in NS0, NS1, NS2 and NS3, respectively.

Regions D1, D2, D3 and D4 represent SGD transistors and regions S1, S2, S3 and S4 represent SGS transistors in SGL1.

FIG. 3A depicts a top view of an example word line layer **304** of the block BLK0 of FIG. 1A, in a straight NAND string embodiment. In this configuration, a NAND string has only one column, and the source-side select gate is on the bottom of the column instead of on the top, as in a U-shaped NAND string. Moreover, a given level of a block has one WLL which is connected to each of the memory cells of the layer. Insulation-filled slits **346, 347, 348, 349** and **350** can also be used in the fabrication process to provide structural support for the stack when undoped polysilicon layers are removed by a wet etch and a dielectric is deposited to form the alternating dielectric layers. A dashed line **305** extends through columns C12-C17. A cross-sectional view along line **305** of portion **307** is shown in FIG. 3C1.

Regions **340, 341, 342, 343, 344** and **345** represent the memory cells (as circles) of respective sets of NAND strings. For example, region **340** represents memory cells in NAND strings NS0A, . . . , NS0A-14. Additional NAND strings include NS1A, NS2A, NS3A, NS4A and NS5A.

Alternatively, the layer **304** represents an SGS layer, in which case each circle represents an SGS transistor.

FIG. 3B depicts a top view of an example SGD layer **362**, consistent with FIG. 3A. Slits **357, 358, 359, 360** and **361**

divide the SGD layer into portions **363, 364, 365, 366, 367** and **368**. Each portion connects the SGD transistors in a set of NAND strings. For example, SGD layer portion **363** or line connects the SGD transistors in the set of NAND strings NS0A to NS0A-14. Regions **351, 352, 353, 354, 355** and **356** represent the SGD transistors (as circles) of respective sets of NAND strings in the SGD layer portions **363, 364, 365, 366, 367** and **368**, respectively. The portion **307** from FIG. 3A is also repeated. The select gate transistors are associated with NAND strings NS0A-NS5A.

FIG. 3C1 depicts an embodiment of a stack **376** showing a cross-sectional view of the portion **307** of FIG. 3A, along line **305**, where three SGD layers, three SGS layers and dummy word line layers DWLL1 and DWLL2 are provided. Columns of memory cells corresponding to NAND strings NS0A-NS3A are depicted in the multi-layer stack. The stack includes a substrate **101**, an insulating film **250** on the substrate, and a portion of a source line SL0A. Additional straight NAND strings in a SGD line subset extend behind the NAND strings depicted in the cross-section, e.g., along the x-axis. NS0A has a source end SEa and a drain end DEa. The slits **346, 347** and **348** from FIG. 3A are also depicted. A portion of the bit line BL0A is also depicted. A conductive via **373** connects DEa to BL0A. The columns are formed in memory holes MH0-MH4. The memory holes are columnar and extend at least from a top **370** to a bottom **371** of the stack.

The source line SL0A is connected to the source ends of each NAND string. SL0A is also connected to other sets of memory strings which are behind these NAND strings in the x direction.

Word line layers, e.g., WLL0-WLL23, and dielectric layers, e.g., DL0-DL24, are arranged alternately in the stack. SGS transistors **369, 372, 374** and **375** are formed in the SGS1 layer.

A region **246** of the stack is shown in greater detail in FIG. 4A.

A region **410** of the stack is shown in greater detail in FIG. 4D.

Regions D1a, D2a, D3a and D4a represent SGD transistors.

FIG. 3C2 depicts a variation in the width of a memory hole along its height. Due to the etching process used to create the memory holes, the cross-sectional width, e.g., diameter, of the memory hole can vary along its height. This is due to the very high aspect ratio. For example, a depth-to-diameter ratio of about 25-30 is common. Typically, the diameter becomes progressively smaller from the top to the bottom of the memory hole. In some case, a slight narrowing occurs at the top of the hole, as depicted, so that the diameter becomes slight wider before becoming progressively smaller from the top to the bottom of the memory hole.

Due to the non-uniformity in the width of the memory hole, and the width of the vertical pillar which is formed in the memory hole, the programming and erase speed of the memory cells can vary based on their position along the memory hole. With a smaller diameter memory hole, the electric field across the tunnel oxide is stronger, so that the programming and erase speed is higher.

FIG. 4A depicts a view of the region **246** of FIG. 3C1, showing SGD transistors D1a, D1a1 and D1a2 above a dummy memory cell (DMC) and a data-storing memory cell (MC). A number of layers can be deposited along the side-walls of the column and within each word line layer. These layers can include oxide-nitride-oxide (O—N—O) and polysilicon layers which are deposited, e.g., using atomic layer deposition. For example, the column includes a charge-trapping layer or film (CTL) **403** such as SiN or other nitride, a

tunnel oxide (TOx) **404**, a polysilicon body or channel (CH) **405**, and a dielectric core (DC) **406**. A word line layer includes a block oxide (BOx) **402**, a block high-k material **401**, a barrier metal **400**, and a conductive metal such as W **399** as a control gate. For example, control gates CG1a, CG1a1, CG1a2, CG1a3 and CG1a4 are provided for the SGD transistors D1a, D1a1 and D1a2, the dummy memory cell DMC and the memory cell MC, respectively. In another approach, all of these layers except the metal are provided in the column. Additional memory cells are similarly formed throughout the columns. The layers in the memory hole form a columnar active area (AA) of the NAND string.

The use of one or more dummy memory cells between the select gate transistors and the data-storing memory cells is useful since program disturb can be greater for memory cells adjacent to, or close to, the select gate transistors. These edge cells have a lower amount of channel boosting due to constraints on the voltages of the select gate transistors of an inhibited NAND string. In particular, to provide the select gate transistors in a non-conductive state, a relatively low voltage is applied to their control gates, resulting in a relatively lower amount of channel boosting in a region of the channel next to these select gate transistors. A region of the channel next to an edge cell will therefore also have a relatively lower amount of channel boosting. In contrast, the cells next to a non-edge cell can receive a relatively high pass voltage since these cells are provided in a conductive state, resulting in a relatively higher amount of channel boosting.

When a memory cell is programmed, electrons are stored in a portion of the CTL which is associated with the memory cell. These electrons are drawn into the CTL from the channel, and through the TOx. The V_{th} of a memory cell is increased in proportion to the amount of stored charge. During an erase operation, the electrons return to the channel.

Each of the memory holes can be filled with a plurality of annular layers comprising a block oxide layer, a charge trapping layer, a tunneling layer and a channel layer. A core region of each of the memory holes is filled with a body material, and the plurality of annular layers are between the core region and the WLLs in each of the memory holes.

FIG. 4B depicts a cross-section view of the region **246** of FIG. 4A along line **444**. Each layer is ring-shaped in one possible approach, except the core filler, which is a cylinder.

FIG. 4C depicts an expanded view of a portion of the SGD transistor D1a of FIG. 4A. An erase operation can involve charging up a channel of the NAND string while floating the voltages of the control gates of the memory cells. This allows the voltages of the control gates of the memory cells to increase with the voltage of the channel due to coupling. The voltages of the control gates of the memory cells are then driven lower, such as to ground or a negative voltage, generating an electric field which drives electrons out of a charge-trapping layer and into the channel, lowering the threshold voltages of the memory cells. This process can be repeated in multiple erase-verify iterations until the threshold voltages of the memory cells are below a desired erase verify level, e.g., V_{v_erase} .

The charging up of the channel occurs due to gate-induced drain leakage (GIDL) of the select gate transistors at the drain and/or source ends of the NAND string. The select gate transistors are reversed biased, e.g., with a positive drain-to-gate voltage, which results in the generation of electron-hole pairs. For example, at the drain end of a NAND string, a bit line voltage (erase pulse) is applied which exceeds a voltage at the control gate of a drain-side select gate transistor by a few Volts. Similarly, at the source end of a NAND string, a source line voltage is applied which exceeds a voltage at the control

gate of a source-side select gate transistor. The electrons are swept away by the electrical field and collected at the bit line and/or source line terminals; while holes will drift to the channel and help to charge up the channel. That is, the electrons will drift toward the high voltage of the bit line or source line, while the holes will drift toward a low voltage.

GIDL results in the generation of electron-hole pairs, including example electrons **450** and holes **451**. As indicated by the arrows, the electrons are attracted to the high erase voltage at the drain or source end of the NAND string while the holes are attracted to a lower voltage region of the channel. When multiple select gate transistors are used at one end of a NAND string, each select gate transistor can generate a similar amount of GIDL. Additionally, one or more dummy memory cells can receive a bias which is similar to the bias of the select gate transistor and generate GIDL. A one-sided or two-sided erase may be used. In a one sided erase, one or more select gate transistors at the drain end of the NAND string, and optionally, one or more dummy memory cells at the drain end, are biased to generate GIDL. A two-sided erase augments the GIDL generated at the drain end by also biasing one or more select gate transistors at the source end of the NAND string, and optionally, one or more dummy memory cells at the source end, to generate GIDL. The SGD transistor D1a has a source side SR1a and a drain side DR1a.

The dummy memory cells and the select gate transistors have a threshold voltage which is kept within a fixed range.

FIG. 4D depicts an expanded view of a region **410** of the NAND string of FIG. 3C2. When a program voltage is applied to the control gate of a memory cell via a respective word line, an electric field is generated. In MC0, the electric field causes electrons to tunnel into a region **470** of the charge-trapping layer **403**, from the channel **405**. Similarly, for MC1, the electric field causes electrons to tunnel into a region **460** of the charge-trapping layer **403**, from the channel **405**. The movement of the electrons into the charge-trapping layer is represented by the arrows which point to the left. The electrons are represented by circles with a dash inside the circle.

When a memory cell on a selected word line is subsequently read back, control gate read voltages such as VreadA, VreadB and VreadC are applied to the memory cell while sensing circuitry determines whether the memory cell is in a conductive state. At the same time, a read pass voltage, Vread (e.g., 8-9 V), is applied to the remaining word lines.

However, as mentioned at the outset, the accuracy of the read back operation can be impaired by charge loss in the memory cells. Charge loss is represented by the arrows which point to the right. For example, an electron **452** is an example of a charge which has de-trapped from the charge-trapping region **470**, lowering the V_{th} of MC0. An electron **453** is an example of a charge which remains in the charge-trapping region **470**.

MC1 has a drain DR1b, a source SR1b and a control gate CG1.

FIG. 5A depicts a cross-sectional view in a word line direction of memory cells comprising a flat control gate and charge-trapping regions a 2D example of memory cells in the memory structure **126** of FIG. 1B. Charge-trapping memory can be used in NOR and NAND flash memory device. This technology uses an insulator such as an SiN film to store electrons, in contrast to a floating-gate MOSFET technology which uses a conductor such as doped polycrystalline silicon to store electrons. As an example, a word line (WL) **524** extends across NAND strings which include respective channel regions **506**, **516** and **526**. Portions of the word line provide control gates **502**, **512** and **522**. Below the word line is an inter-poly dielectric (IPD) layer **528**, charge-trapping

layers **504**, **514** and **521**, polysilicon layers **505**, **515** and **525** and tunnel oxide (TOx) layers **509**, **507** and **508**. Each charge-trapping layer extends continuously in a respective NAND string.

A memory cell **500** includes the control gate **502**, the charge-trapping layer **504**, the polysilicon layer **505** and a portion of the channel region **506**. A memory cell **510** includes the control gate **512**, the charge-trapping layer **514**, a polysilicon layer **515** and a portion of the channel region **516**. A memory cell **520** includes the control gate **522**, the charge-trapping layer **521**, the polysilicon layer **525** and a portion of the channel region **526**.

Further, a flat control gate may be used instead of a control gate that wraps around a floating gate. One advantage is that the charge-trapping layer can be made thinner than a floating gate. Additionally, the memory cells can be placed closer together.

FIG. **5B** depicts a cross sectional view along line **559** in FIG. **5A**, showing a NAND string **530** having a flat control gate and a charge-trapping layer. The NAND string **530** includes an SGS transistor **531**, example storage elements **500**, **532**, . . . , **533** and **534**, and an SGD transistor **535**. The SGD transistor can be biased to produce GIDL during an erase operation, as discussed. The memory cell **500** includes the control gate **502** and an IPD portion **528** above the charge-trapping layer **504**, the polysilicon layer **505**, the tunnel oxide layer **509** and the channel region **506**. The memory cell **532** includes a control gate **536** and an IPD portion **537** above the charge-trapping layer **504**, the polysilicon layer **505**, the tunnel oxide layer **509** and the channel region **506**.

The control gate layer may be polysilicon and the tunnel oxide layer may be silicon oxide, for instance. The IPD layer can be a stack of high-k dielectrics such as AlOx or HfOx which help increase the coupling ratio between the control gate layer and the charge-trapping or charge storing layer. The charge-trap layer can be a mix of silicon nitride and oxide, for instance. A difference between a floating gate memory cell and the flat memory cell is the height of the charge storage layer. A typically floating gate height may be about 100 nm, while a charge-trap layer can be as small as 3 nm, and the polysilicon layer can be about 5 nm. The SGD and SGS transistors have the same configuration as the storage elements but with a longer channel length to ensure that current is cutoff in an inhibited NAND string.

FIG. **5C** depicts an expanded view of a portion **540** of the NAND string of FIG. **5B**. The charge-trapping layer **504** includes regions **541** and **543** which are directly under and adjacent to the memory cells **500** and **532**, respectively.

Charge loss can occur in a 2D memory device in a similar way as in the 3D memory device. Charge loss is represented by the arrows which point downward. For example, an electron **551** is an example of a charge which has de-trapped from the charge-trapping region **541**, lowering the V_{th} of the memory cell **500**. An electron **552** is an example of a charge which remains in the charge-trapping region **541**.

FIG. **6A** is a plot of V_{th} versus time, showing a decrease in V_{th} after a memory cell is programmed due to short-term charge loss. The horizontal axis depicts time on a logarithmic scale and the vertical axis depicts the V_{th} of a memory cell. After the memory cell is programmed to an initial V_{th} of its target data state, its V_{th} gradually decreases. The rate of decrease is a function of the data state, such that the rate is smaller when the V_{th} of the data state is higher. This is because the memory cells with the higher data states receive a larger number of program pulses before they complete programming, compared to memory cells with the lower data states. The additional program pulses accelerate hole redi-

tribution in the charge-trapping material before the memory cells with the higher data states have completed programming. Further, relatively high magnitude program pulses are used which stress the gate stacks of the memory cells with the higher data states, also accelerating hole redistribution.

FIG. **6B** depicts an energy band diagram for a memory cell. The horizontal axis depicts a distance in the memory cell. For example, this can be a lateral distance in a 3D memory device or a vertical distance in a 2D memory device. The vertical axis depicts an energy level. The memory cell includes a channel region (CH), a tunnel oxide region (TOx), a charge-trapping layer (CTL), a block oxide (BOx) and a control gate (CG). Example holes **610** in the CTL are also depicted. This is a band diagram at a flatband condition after erase, and represents how the holes are redistributed in the CTL due to the use of a positive control gate voltage after erase, as described herein. By causing the redistribution before programming, the redistribution which occurs after the cell is programmed so that changes in the V_{th} of the cell are reduced.

FIG. **7A** depicts a circuit diagram of a NAND string consistent with the memory devices of FIGS. **2C** and **3C1**. An example NAND string NS0A, consistent with FIG. **3C1** (or NS0 consistent with FIG. **2C**), includes SGD transistors **701**, **702** and **703**, a drain-side dummy memory cell **704**, data-storing memory cells **705**, . . . , **706**, a source-side dummy memory cell **707**, and SGS transistors **708**, **709** and **710**. A bit line **712** connects the drain end of the NAND string to sensing circuitry **700**, which is used to sense the NAND string during operations involving the select gate transistors and the memory cells. A source line **711** is connected to a source end of the NAND string. Voltage drivers can be used to provide the voltages depicted. For example, V_{sg} is applied to the control gates of the SGD transistors, which are connected to one another and to the control gates of the SGS transistors, which are connected to one another. V_{sg} can also be applied to the dummy memory cells **704** and **707**. A common word line voltage V_{wl} is applied to each of the data-storing memory cells, in this example. V_{bl} is the bit line voltage and V_{sl} is the source line voltage. I_{NAND} is a sensed current in the NAND string.

FIG. **7B** depicts a plot of V_{th} versus I_{NAND} , a current in a NAND string during a sensing operation. An erase operation can include a number of erase-verify iterations which are performed until the erase operation is completed. An erase-verify iteration includes an erase portion in which an erase voltage is applied, followed by a verify test. While it possible to verify memory cells in one or more selected word lines, typically an entire block is erased, in which case the verification can be performed concurrently for all memory cells in one or more NAND strings. During a verify operation for the memory cells of a NAND string, a verify voltage (V_{v_erase}) is applied to the control gates of the memory cells while a bit line voltage is supplied using sensing circuitry. The select gate transistors and dummy memory cells are provided in a conductive state and act as pass gates. A current in the NAND string is detected and compared to a reference current, e.g., using a current comparison circuit. If the current in the NAND string exceeds the reference current, this indicates the cells in the NAND string are in a conductive state, so that their V_{th} is below V_{v_erase} . That is, all of the cells in the NAND string are erased and the NAND string passes the verify test. On the other hand, if the current in the NAND string does not exceed the reference current, this indicates the cells in the NAND string are in a non-conductive state, so that their V_{th} is above V_{v_erase} . That is, not all of the cells in the NAND string are erased and the NAND string does not pass the verify test.

In one approach, the memory device has the capability to apply V_{v_erase} as a negative voltage on the word lines, such as by using a negative charge pump. In this case, the drain (bit line) and source can be set at 0 V, and there is a positive source-to-control gate voltage of the memory cells. For example, with $V_{v_erase} = -2$ V and $V_{source} = 0$ V, $V_{source} - V_{v_erase} = 0 - (-2) = 2$ V. In other cases, it may be desired to apply a zero or positive control gate voltage during sensing. To do this, V_{source} can be elevated so that there is still a positive source-to-control gate voltage. For example, with $V_{v_erase} = 0$ V and $V_{source} = 2$ V, $V_{source} - V_{v_erase} = 2 - (0) = 2$ V, as before. The same V_{th} in a memory cell can therefore be sensed without using a negative control gate voltage.

For a set of NAND strings, the erase operation can be considered to be completed when all, or at least a specified majority, of the NAND strings pass the verify test. If the erase operation is not completed after an erase-verify iteration, another erase-verify iteration can be performed using a stronger erase voltage.

FIG. 8A depicts an example erase operation in which the memory cells are biased to accelerate the redistribution of holes. Step 800 begins an erase operation for a set of memory cells such as in a block. Step 801 involves performing an erase portion of an erase-verify iteration. See also FIG. 9A. Step 802 involves performing a verify test. See also FIG. 7B. Decision step 803 determines whether the memory cells pass the verify test. If decision step 803 is false, a count of erase-verify iterations is incremented at step 804 and the erase portion of a next erase-verify iteration is performed at step 801. If decision step 803 is true, step 805 determines an erase depth. See also FIG. 10D. Step 806 biases the memory cells to accelerate the redistribution of holes, e.g., by applying a positive control gate voltage. See also FIG. 8C. In one approach, a common positive control gate voltage is applied concurrently to each memory cell in a set of memory cells via the respective word lines.

In another approach, the vertical pillars of the NAND strings have varying cross-sectional widths along a height of a three-dimensional memory structure, the positive control gate voltage has a duration which is a function of a height of a selected word line in the memory device, and the duration is relatively shorter when the height is associated with a relatively smaller cross-sectional width of the vertical pillars.

Step 807 ends the erase operation. Step 808 involves performing a programming operation.

Typically, an erase operation is performed in connection with a subsequent programming operation. Thus, the biasing of the memory cells to accelerate the redistribution of holes can be performed in response to one or more commands from a state machine or other control circuit which involve an erase and programming. In another approach, the biasing of the memory cells to accelerate the redistribution of holes can be performed in response to one or more commands which involve an erase. In another approach, the biasing of the memory cells to accelerate the redistribution of holes can be performed in response to one or more commands which involve programming.

FIG. 8B depicts a plot showing an optimal pulse duration (vertical axis) versus a number of erase loops or a number of program-erase (P-E) cycles (horizontal axis), for use in step 805 of FIG. 8A. A relatively high number of program-erase cycles generally results in a deeper erase depth because the memory cells can take larger V_{th} jumps with each erase-verify iteration. Further, a deeper erase results in relatively more holes being injected into the charge-trapping material. As a result, a longer pulse duration is appropriate for the positive control gate voltage in proportion to the number of

program-erase cycles. The magnitude of the positive control gate voltage could be increased as well, but an increase in the duration is more likely to avoid undesired any chance of programming the cells. Similarly, a relatively high number of erase loops (e.g., erase-verify iterations) generally results in a deeper erase depth. As a result, a longer pulse duration is appropriate for the positive control gate voltage in proportion to the number of erase loops.

FIG. 8C depicts an example process for implementing step 806 of FIG. 8A using multiple pulses. Step 810 applies a positive control gate voltage to the memory cells. Step 811 determines an erase depth. See also FIG. 10E. Decision step 812 determines whether the erase depth is sufficiently deep. If decision step 812 is false, step 810 is performed again to apply another positive control gate voltage. This additional positive control gate voltage can have the same duration and magnitude as the initial positive control gate voltage. Or, the duration and/or magnitude can be different. If decision step 812 is true, the process ends at step 813.

FIG. 8D depicts an example programming operation, consistent with step 808 of FIG. 8A. The programming may comprise incremental step pulse programming (ISPP). Step 820 involves initializing V_{pgm} , the program voltage. Step 821 involves applying V_{pgm} to a selected word line, while enabling programming of all memory cells which have not completed programming (such as by grounding bit lines which are connected to NAND strings in which these cells are located), and inhibiting programming of memory cells which have completed programming (such as by raising voltages of bit lines which are connected to NAND strings in which these cells are located).

Step 822 involves performing a verify test for memory cells with one or more target data states using verify voltages (e.g., V_{vA} , V_{vB} or V_{vC} ; see FIG. 10A). Decision step 823 determines if programming of the set of memory cells is completed. This is true when all, or almost all, of the memory cells have passed their respective verify test. If decision step 823 is false, V_{pgm} is incremented at step 824 and step 821 is repeated in a next program-verify iteration. If decision step 823 is true, the programming ends at step 825.

FIG. 9A depicts an example erase waveform 900 for use in step 801 of FIG. 8A. The erase operation comprises a series of program-erase iterations EV1, EV2, EV3 and EV4. Four erase-verify iterations are shown as an example. One or more can be used. In the first erase-verify iteration EV1, an erase voltage waveform 910 is applied to a bit line and/or source line of each selected NAND string (e.g., each NAND string which has one or more memory cells to be erased), and a select gate waveform 911 is applied to the select gate transistors. The erase voltage waveform 910 has a peak level of V_{er_pk1} . The select gate waveform 911 has a peak level of V_{sg_pk1} . A step size for the erase voltage waveform is $dVer$.

In the second erase-verify iteration EV2, an erase voltage waveform 920 has a peak level of V_{er_pk2} . The select gate waveform 921 has a peak level of V_{sg_pk2} .

In the third erase-verify iteration EV3, an erase voltage waveform 930 has a peak level of V_{er_pk3} . The select gate waveform 931 has a peak level of V_{sg_pk3} .

In the fourth erase-verify iteration EV4, an erase voltage waveform 940 has a peak level of V_{er_pk4} . The select gate waveform 941 has a peak level of V_{sg_pk4} .

Further, verify operations V_{ver1} , V_{ver2} , V_{ver3} and V_{ver4} are performed in the erase-verify iterations EV1, EV2, EV3 and EV4, respectively.

In this example, the peak levels of the select gate voltage and the erase voltage are stepped up together so that there is a fixed difference between them. This provides a consistent

drain-to-gate voltage which results in a consistent amount of GIDL and charge up of the channel. However, other approaches are possible. For example, the peak level of the select gate voltage may be fixed. In another option, the erase voltage steps up to its peak in two steps instead of one to allow time for the charge up of the channel to occur. In another option, the erase voltage and the select gate voltage both step up to their peaks in two steps.

Any unselected NAND strings can be inhibited from being erased by allowing the voltages of the select gate transistors to float, for instance, so that their channels are not charged up.

Note that while two-step waveforms are provided, other variations are possible. For example, generally, a multi-step waveform comprising two or more steps can be used. In another variation, the waveforms comprise ramps instead of, or in addition to, steps.

FIG. 9B depicts a detailed view of the waveforms **910** and **911** of FIG. 9A in addition to a waveform **912** which represents a voltage of a channel (V_{ch}) of a NAND string, and a waveform **913** which represents a voltage of a control gate of a memory cell or an associated word line (V_{wl}). The horizontal axis depicts time and the vertical axis depicts voltage. Before t_1 , the waveforms are at 0 V. From t_1 - t_2 , the erase voltage waveform is increased to a peak level, V_{er_pk1} , and the select gate waveform is increased to a peak level, V_{sg_pk1} . At this time, GIDL begins to occur in proportion to the drain-to-gate voltage ($V_{er_pk1}-V_{sg_pk1}$) of the select gate transistors. Between t_2 and t_3 , the channel continues to charge up, and remains at a peak charged level from t_3 - t_4 . V_{wl} (waveform **913**) is floating so that it is coupled up by V_{ch} to a level which is slightly below V_{ch} .

For the selected word lines, waveform portion **913a** indicates that the word line voltage is driven lower, e.g., to 0 V, driving electrons out of the charge trapping layer and into the channel, thus erasing the associated memory cells. For the unselected word lines, if any, waveform portion **913b** indicates that the word line voltage remains floating so that no erasing occurs for the associated memory cells. Between t_5 and t_6 , the select gate waveform and the erase voltage waveform are reduced to 0 V. V_{ch} and V_{wl} follow to 0 V.

FIG. 9C depicts voltages applied to a word line in a programming operation, consistent with step **808** of FIG. 8A. The horizontal axis depicts time or program loops and the vertical axis depicts V_{WLn} , the voltage on an n th word line which is selected for programming. The programming pass comprises a series of waveforms **960**. ISPP is performed for each target data state. This example also performs verify tests based on the program loop. For example, the A, B and C state cells are verified in loops **1-4**, **3-7** and **5-9**, respectively. An example verify waveform **961** comprises an A state verify voltage at V_{vA} . An example verify waveform **962** comprises A and B state verify voltages at V_{vA} and V_{vB} , respectively. An example verify waveform **963** comprises B and C state verify voltages at V_{vB} and V_{vC} , respectively. An example verify waveform **964** comprises a C state verify voltage at V_{vC} . The program pulses **P1** (with amplitude V_{pgm_init} and duration t_p), **P2**, **P3**, **P4**, **P5**, **P6**, **P7**, **P8** and **P9** are also depicted.

The positive control gate voltage **950** with a duration of t_{pulse} and an amplitude of V_{pulse} is also depicted. Recall that this voltage can be applied in connection with an erase operation which precedes the programming operation.

Generally, the positive control gate voltage can be adjusted in magnitude and duration to optimize the amount of hole redistribution. The positive control gate voltage should result in lowering of the lower tail of the V_{th} distribution of the erased state without raising the upper tail. However, in some

cases, some raising of the upper tail may be acceptable. The raising of the upper tail reduces the space between the V_{th} distributions of the erased state and the A state, which in turn lowers the V_{th} window.

As an example, the magnitude can be 5 V and the duration can be 1 milliseconds for a fresh memory device and 2 milliseconds for a cycled memory device. In one approach, the positive control gate voltage has a magnitude which is less than one half or one third of an initial program voltage (V_{pgm_int} , e.g., 15-18 V) of the incremental step pulse programming and has a duration which is at least five, ten or twenty times longer than a duration of the initial program voltage (e.g., 10-40 microseconds).

Additionally, when the positive control gate voltage is applied to a memory cell, the drain of each memory cell can be set by a voltage of a bit line connected to a NAND string in which the memory cell is located. If the bit line is grounded, the gate-to-drain voltage is equal to the positive control gate voltage. The applying of a positive control gate voltage can therefore be considered to be the same as applying a positive control gate-to-drain voltage.

Moreover, the memory cells of a set of memory cells may be arranged in a set of NAND strings, where each NAND string of the set of NAND strings is connected to a bit line in a set of bit lines. The providing of the positive control gate-to-drain voltage for each memory cell in the set of memory cells can comprise setting each bit line in the set of bit lines to a fixed level (e.g., 0 V) which is less than the positive control gate voltage.

FIG. 10A depicts V_{th} distributions of a set of memory cells, showing a decrease in V_{th} due to charge loss, and a subsequent erase operation, consistent with steps **801** and **802** of FIG. 8A. In FIG. 10A to 10F, the horizontal axis depicts V_{th} and the vertical axis depicts a number of memory cell, on a logarithmic scale. A set of memory cells is initially programmed from an erased state to target data states of A, B and C using verify voltages of V_{vA} , V_{vB} and V_{vC} , respectively, in a four state memory device. In other cases, eight, sixteen or more data states are used. The erased state and the A, B and C states are represented by V_{th} distributions **1000**, **1010**, **1020** and **1030**, respectively. After programming, short-term charge loss occurs due to the redistribution of holes in the charge-trapping material of the memory cells, so that the V_{th} distributions **1010**, **1020** and **1030** shift down and widen to become the V_{th} distributions **1011**, **1021** and **1031**, respectively. The memory cells are subsequently erased using the verify voltage of V_{v_erase} .

FIG. 10B depicts a decrease in the lower tail of the V_{th} distribution of the erased state due to biasing of memory cells to accelerate redistribution of holes, consistent with step **806** of FIG. 8A. In this case, the V_{th} distribution **1000** becomes wider due to the lower tail of the V_{th} distribution becoming lower, resulting in the V_{th} distribution **1001**. This result is contrasted with soft programming in which the lower tail become higher. In one approach, soft programming is not used.

FIG. 10C depicts V_{th} distributions of a set of memory cells after programming, consistent with step **808** of FIG. 8A. Starting from the erased state V_{th} distribution **1001**, the memory cells are programmed to the A, B and C state V_{th} distributions **1010**, **1020** and **1030**, respectively, as in FIG. 10A. However, since the hole redistribution was accelerated by the positive control gate voltage, the V_{th} distributions remain above the respective verify levels and the downshifted V_{th} distributions **1011**, **1021** and **1031** of FIG. 10A are avoided.

FIG. 10D depicts a portion of the V_{th} distribution of the erased state for which memory cells have a $V_{th} < V1$, before biasing of memory cells to accelerate redistribution of holes, consistent with step 805 of FIG. 8A. When the erase-verify iterations are completed, the lower tail of the V_{th} distribution of the erased state can be measured. $V1$ is an example voltage which is expected to be within the lower tail. $V1$ is applied to the memory cells while a current through the NAND string is sensed. The NAND strings which have memory cells with a $V_{th} < V1$ (based on the sensed NAND string current being above a reference current) are represented by the region 1000a of the V_{th} distribution 1000. The lower tail can be considered to be relatively lower (and the erase relatively deeper) when a portion of the NAND strings which have cells with a $V_{th} < V1$ is relatively greater. For example, if there are 100 NAND strings being erased, and 10 of them have cells with a $V_{th} < V1$, then the extent of the lower tail below $V1$ is relatively small. On the other hand, if there are 100 NAND strings being erased, and 40 of them have cells with a $V_{th} < V1$, then the extent of the lower tail below $V1$ is relatively large and the erase is relatively deeper.

As mentioned, the positive control gate voltage can be adjusted based on the depth of the erase.

FIG. 10E depicts a portion of the V_{th} distribution of the erased state for which memory cells have a $V_{th} < V1$, after biasing of memory cells to accelerate redistribution of holes, consistent with step 811 of FIG. 8C. In this case, the depth of the erase is determined after a positive control gate voltage is applied, to ascertain the effect of the positive control gate voltage and to determine whether an additional positive control gate voltage should be applied. The V_{th} distribution 1000 from FIG. 10A is repeated. The V_{th} distribution 1001 is obtained after a first positive control gate voltage. Again, note the lowering of the lower tail of the V_{th} distribution when a positive control gate voltage is applied.

As before, $V1$ is applied to the memory cells while a current through the NAND string is sensed. The NAND strings which have cells with a $V_{th} < V1$ are represented by the region 1001a of the V_{th} distribution 1001. If a portion of the NAND strings which have cells with a $V_{th} < V1$ is above a specified portion of all NAND strings involved in the erase operation, it may be concluded that the V_{th} distribution of the erased state has been sufficiently lowered (e.g., the erase depth of the set of memory cells is sufficiently deep) by the first positive control gate voltage, so that no further positive control gate voltage should be used. On the other hand, if the portion of the NAND strings which have cells with a $V_{th} < V1$ is below a specified portion of all NAND strings involved in the erase operation, it may be concluded that the V_{th} distribution of the erased state has not been sufficiently lowered (e.g., the erase depth of the set of memory cells is not sufficiently deep) by the first positive control gate voltage, so that an additional positive control gate voltage should be used.

FIG. 10F depicts a decrease in the lower tail of the V_{th} distribution of the erased state in multiple steps, consistent with FIG. 8C. The initial V_{th} distribution 1000 of the erased state is repeated. A first positive control gate voltage is applied, resulting in a lowering of the V_{th} distribution of the erased state from the V_{th} distribution 1000 to the V_{th} distribution 1001. A second positive control gate voltage is also applied, resulting in a further lowering of the V_{th} distribution of the erased state from the V_{th} distribution 1001 to the V_{th} distribution 1002, due to further hole redistribution in the charge-trapping material.

Accordingly, it can be seen that, in one embodiment, a method for operating a memory device comprises: performing a plurality of erase-verify iterations for a set of memory

cells connected to a set of word lines until a verify test is passed by the set of memory cells, each memory cell of the set of memory cells comprises a charge-trapping material, the verify test determines whether memory cells of the set of memory cells have a threshold voltage which is below a verify voltage, and the set of memory cells has the threshold voltage distribution when the verify test is passed by the set of memory cells; and after the verify test is passed by the set of memory cells, biasing the set of memory cells to cause a lower tail of the threshold voltage distribution to move lower, the biasing the set of memory cells comprises providing a positive control gate-to-drain voltage for each memory cell in the set of memory cells.

In another embodiment, a memory device comprises: a set of memory cells connected to a set of word lines, each memory cell of the set of memory cells comprises a charge-trapping material; and a control circuit. The control circuit: performs an erase operation for the set of memory cells, wherein the set of memory cells has a threshold voltage distribution when the erase operation is completed, after the erase operation, performs biasing of the set of memory cells to cause a lower tail of the threshold voltage distribution to move lower by applying a positive control gate voltage to each word line of the set of word lines, and after the biasing of the set of memory cells, programs selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming, the incremental step pulse programming comprises an initial program voltage which is applied to the selected word line, wherein the positive control gate voltage has a magnitude which is less than one half of an initial program voltage of the incremental step pulse programming and has a duration which is at least ten times longer than a duration of the initial program voltage.

In another embodiment, a memory device comprises: a set of memory cells connected to a set of word lines, each memory cell of the set of memory cells comprises a charge-trapping material; and a control circuit. The control circuit is configured to: perform a plurality of erase-verify iterations for the set of memory cells until a verify test is passed by the set of memory cells, each memory cell of the set of memory cells comprises a charge-trapping material, the verify test determines whether memory cells of the set of memory cells have a threshold voltage which is below a verify voltage, and the set of memory cells has a threshold voltage distribution when the verify test is passed by the set of memory cells, count a number of erase-verify iterations in the plurality of erase-verify iterations, and after the verify test is passed by the set of memory cells, apply a positive control gate voltage to each word line of the set of word lines, wherein the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

In another embodiment, a memory device comprises: a set of memory cells connected to a set of word lines, each memory cell of the set of memory cells comprises a charge-trapping material; and a control circuit. The control circuit is configured to perform a plurality of erase-verify iterations for the set of memory cells until a verify test is passed by the set of memory cells, the verify test determines whether memory cells of the set of memory cells have a threshold voltage which is below a verify voltage, and the set of memory cells has a threshold voltage distribution when the verify test is passed by the set of memory cells, and after the verify test is passed by the set of memory cells, the control circuit is configured to bias the set of memory cells to cause a lower tail of the threshold voltage distribution to move lower, the bias of

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the set of memory cells is achieved by providing a positive control gate-to-drain voltage for each memory cell in the set of memory cells.

The foregoing detailed description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The described embodiments were chosen in order to best explain the principles of the invention and its practical application, to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

What is claimed is:

1. A method for operating a memory device, comprising: performing a plurality of erase-verify iterations for a set of memory cells connected to a set of word lines until a verify test is passed by the set of memory cells, each memory cell of the set of memory cells comprises a charge-trapping material, the verify test determines whether memory cells of the set of memory cells have a threshold voltage which is below a verify voltage, and the set of memory cells has a threshold voltage distribution when the verify test is passed by the set of memory cells; and after the verify test is passed by the set of memory cells, biasing the set of memory cells to cause a lower tail of the threshold voltage distribution to move lower, the biasing the set of memory cells comprises providing a positive control gate-to-drain voltage for each memory cell in the set of memory cells.
2. The method of claim 1, further comprising: after the biasing of the set of memory cells, programming selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming, the incremental step pulse programming comprises an initial program voltage which is applied to the selected word line; wherein: the providing the positive control gate-to-drain voltage for each memory cell in the set of memory cells comprises applying a positive control gate voltage to each word line of the set of word lines; and the positive control gate voltage has a magnitude which is less than one half of an initial program voltage of the incremental step pulse programming and has a duration which is at least ten times longer than a duration of the initial program voltage.
3. The method of claim 2, wherein: the programming of the selected memory cells occurs without soft programming of the selected memory cells.
4. The method of claim 1, wherein: the memory cells of the set of memory cells are arranged in a set of NAND strings; each NAND string of the set of NAND strings is connected to a bit line in a set of bit lines; and the providing the positive control gate-to-drain voltage for each memory cell in the set of memory cells comprises setting each bit line in the set of bit lines to a fixed level which is less than the positive control gate voltage.
5. The method of claim 1, further comprising, after the biasing of the set of memory cells, programming selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines, wherein:

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the providing the positive control gate-to-drain voltage for each memory cell in the set of memory cells comprises applying a positive control gate voltage to each word line of the set of word lines;

the memory cells of the set of memory cells are arranged along vertical pillars which extend in a three-dimensional memory structure;

the vertical pillars have varying cross-sectional widths along a height of the three-dimensional memory structure;

the positive control gate voltage has a duration which is a function of a height of the selected word line in the memory device; and

the duration is relatively shorter when the height is associated with a relatively smaller cross-sectional width of the vertical pillars.

6. The method of claim 1, wherein the providing the positive control gate-to-drain voltage for each memory cell in the set of memory cells comprises applying a positive control gate voltage to each word line of the set of word lines, the method further comprising:

counting a number of erase-verify iterations in the plurality of erase-verify iterations which are used before the verify test is passed by the set of memory cells, wherein the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

7. The method of claim 1, further comprising: maintaining a count of program-erase cycles of the set of memory cells, wherein the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

8. The method of claim 1, further comprising: sensing a position of the lower tail of the threshold voltage distribution, wherein the positive control gate voltage has a duration which is relatively shorter when the position is relatively higher.

9. The method of claim 1, wherein: the providing the positive control gate-to-drain voltage for each memory cell in the set of memory cells comprises providing a first control gate-to-drain voltage for a memory cell in the set of memory cells, followed by determining an erase depth of the set of memory cells, followed by providing a second control gate-to-drain voltage for the memory cell in the set of memory cells if the erase depth of the set of memory cells is not sufficiently deep.

10. The method of claim 9, wherein: the memory cells of the set of memory cells are arranged in NAND strings; and the determining the erase depth comprises sensing currents in the NAND strings and comparing the currents to a reference current, wherein the currents are indicative of threshold voltage levels.

11. The method of claim 10, further comprising: during the sensing of the currents in the NAND strings, providing a positive source-to-control gate voltage of the memory cells of the set of memory cells.

12. A memory device, comprising: a set of memory cells connected to a set of word lines, each memory cell of the set of memory cells comprises a charge-trapping material; and a control circuit, the control circuit: performs an erase operation for the set of memory cells, wherein the set of memory cells has a threshold voltage distribution when the erase operation is completed,

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after the erase operation, performs biasing of the set of memory cells to cause a lower tail of the threshold voltage distribution to move lower by applying a positive control gate voltage to each word line of the set of word lines, and

after the biasing of the set of memory cells, programs selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming, the incremental step pulse programming comprises an initial program voltage which is applied to the selected word line, wherein the positive control gate voltage has a magnitude which is less than one half of an initial program voltage of the incremental step pulse programming and has a duration which is at least ten times longer than a duration of the initial program voltage.

13. The memory device of claim **12**, wherein the erase operation comprises a plurality of erase-verify iterations, the erase operation is completed when a verify test is passed by the set of memory cells, and the control circuit is configured to:

count a number of erase-verify iterations in the plurality of erase-verify iterations which are used before the verify test is passed by the set of memory cells, wherein the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

14. The memory device of claim **12**, wherein:

the memory cells of the set of memory cells are arranged along vertical pillars which extend in a three-dimensional memory structure;

the vertical pillars have varying cross-sectional widths along a height of the three-dimensional memory structure;

the positive control gate voltage has a duration which is a function of a height of the selected word line in the memory device; and

the duration is relatively shorter when the height is associated with a relatively smaller cross-sectional width of the vertical pillars.

15. The memory device of claim **12**, wherein:

the control circuit maintains a count of program-erase cycles of the set of memory cells; and

the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

16. The memory device of claim **12**, wherein:

after the applying the positive control gate voltage to each word line of the set of word lines, the control circuit determines an erase depth of the set of memory cells, and applies an additional control gate voltage to each word line of the set of word lines if the erase depth of the set of memory cells is not sufficiently deep.

17. A memory device, comprising:

a set of memory cells connected to a set of word lines, each memory cell of the set of memory cells comprises a charge-trapping material; and

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a control circuit, the control circuit is configured to:

perform a plurality of erase-verify iterations for the set of memory cells until a verify test is passed by the set of memory cells, each memory cell of the set of memory cells comprises a charge-trapping material, the verify test determines whether memory cells of the set of memory cells have a threshold voltage which is below a verify voltage, and the set of memory cells has a threshold voltage distribution when the verify test is passed by the set of memory cells,

count a number of erase-verify iterations in the plurality of erase-verify iterations, and

after the verify test is passed by the set of memory cells, apply a positive control gate voltage to each word line of the set of word lines, wherein the positive control gate voltage has a duration which is relatively shorter when the count is relatively lower.

18. The memory device of claim **17**, wherein:

after the positive control gate voltage is applied to each word line of the set of word lines, the control circuit is configured to program selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming;

the incremental step pulse programming comprises an initial program voltage which is applied to the selected word line; and

the duration of the positive control gate voltage is at least ten times longer than a duration of the initial program voltage.

19. The memory device of claim **17**, wherein:

after the positive control gate voltage is applied to each word line of the set of word lines, the control circuit is configured to program selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming; and

the control circuit is configured to program the selected memory cells without soft programming of the selected memory cells.

20. The memory device of claim **17**, wherein:

after the positive control gate voltage is applied to each word line of the set of word lines, the control circuit is configured to program selected memory cells of the set of memory cells which are connected to a selected word line of the set of word lines using incremental step pulse programming;

the incremental step pulse programming comprises an initial program voltage which is applied to the selected word line; and

the positive control gate voltage has a magnitude which is less than one half of an initial program voltage of the incremental step pulse programming.

21. The memory device of claim **20**, wherein:

the duration of the positive control gate voltage is at least ten times longer than a duration of the initial program voltage.

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